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PETROLOGY, GEOCHEMISTRY AND GEOCHRONOLOGY OF
A PEGMATITE-GNEISS COMPLEX NEAR VIKING LAKE,
SASKATCHEWAN

by



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A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Petrology, Geochemistry and Geochronology of a Pegmatite-Gneiss Complex Near Viking Lake Saskatchewan", submitted by Gordon Winslow Bird, B.Sc., in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

Samples of gneiss, amphibolite and pegmatite from a small pegmatite-gneiss complex near Viking Lake, northwestern Saskatchewan were studied petrographically and chemically, and were dated by the Rb-Sr and K-Ar methods.

The maximum metamorphic grade attained in the area was the epidote-amphibolite facies. Retrograde metamorphism formed a mixed greenschist and epidote-amphibolite facies assemblage which is present now. A second generation of microcline, quartz and plagioclase was introduced by metasomatic activity late in the metamorphic cycle. The pegmatite probably formed during the period of metasomatic activity. Limited chemical data, and the initial ($\text{Sr}^{87}/\text{Sr}^{86}$) ratios in the pegmatite and gneisses indicate that the pegmatitic material was derived from an external source.

Rb-Sr dating of the rocks gave two isochrons. The gneisses have a metamorphic age of 1934 ± 74 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.714 ± 0.002 . The pegmatite has an age of 1846 ± 40 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.707 ± 0.002 . K-Ar dates of six biotite and hornblende separates range from 1619 to 1892 m.y. The 1619 m.y. date is the minimum date for the last event in the area.

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I INTRODUCTION

Nature of the study

This thesis describes the results of a petrographic, chemical and geochronological study of a small area of banded gneisses containing two small discordant pegmatite bodies. The author mapped the area and collected some sixty samples for further study in the laboratory. A combined petrographic, chemical and geochronological investigation was planned to determine the petrogenetic relationships of the various rock types, the method of emplacement of the pegmatite bodies, and the time sequence of the events in the area.

Thin sections were cut from the samples and were examined with a petrographic microscope. Petrographic descriptions were compiled and a number of interpretations about the geology of the area were made from this data.

The chemical study of the samples was directed toward the elucidation of the petrogenetic relationships of the various rock types. The chemical study included three total rock analyses and a number of partial analyses for major and trace elements. The isotopic composition of strontium in the samples was determined in the process of dating the rocks. The petrogenetic significance of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ in the gneisses and the pegmatites is discussed.

A program of radiometric dating was planned to determine the metamorphic history of the area and the age of the rocks. A Bernard-Price Institute Rb-Sr isochron plot was used to date sixteen whole rock samples representing the major geological phases in the area. The K-Ar age determination method was used to date six biotite and hornblende separates from the pegmatite and amphibolite samples. The results of the dating program are discussed with respect to the regional geological framework of the Lake Athabasca region.

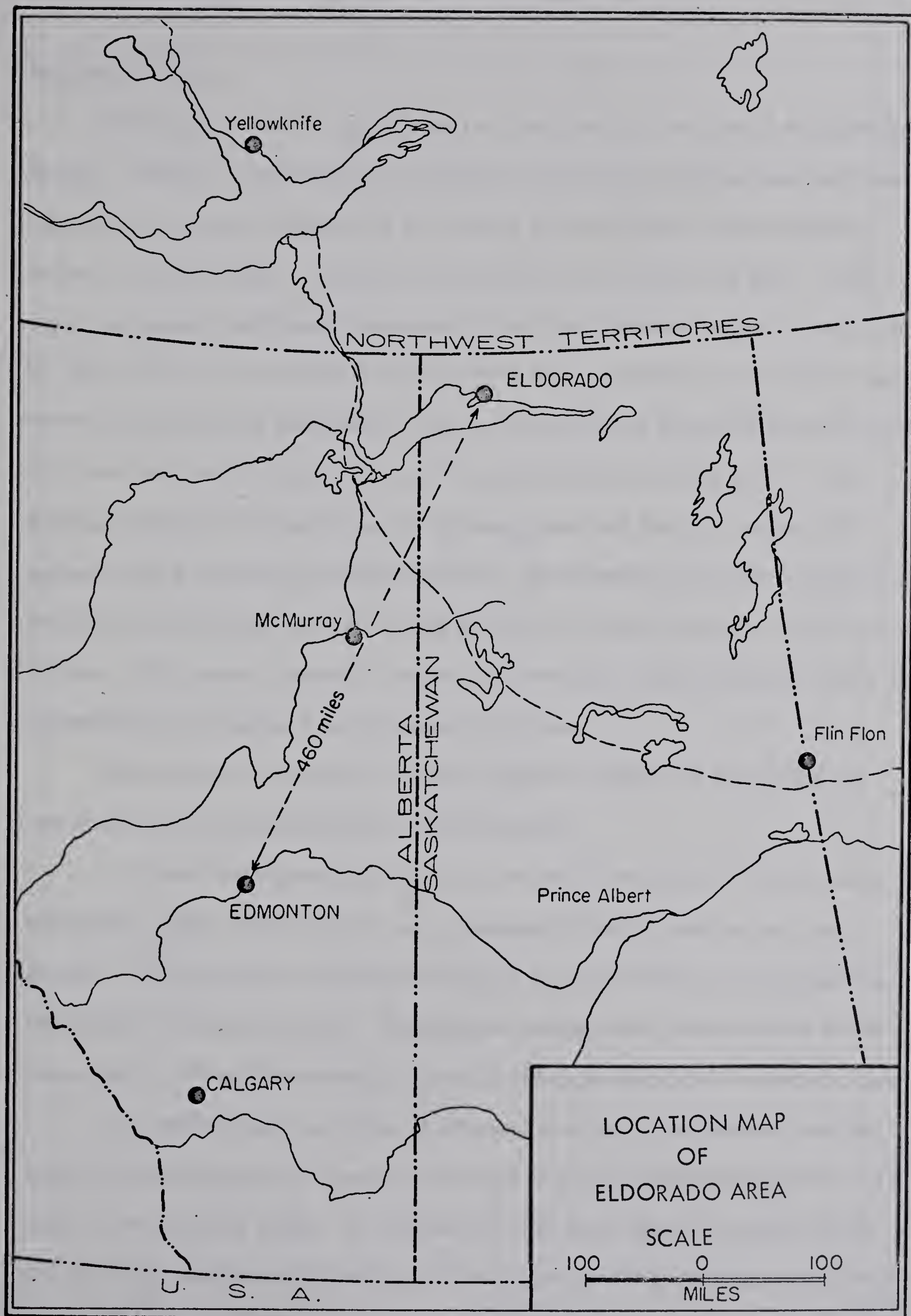
All analytical methods used by the author are described in the appendices at the end of this thesis.

Location and Access

The area selected for this project lies about 12 miles east of Eldorado, Saskatchewan. The area is about 1 mile east of Viking Lake and 1 mile north of Gibbs Lake, (see Figure 2).

The townsite of Eldorado lies in the extreme northwestern part of Saskatchewan on the north shore of Beaverlodge Lake, about 460 air miles north of Edmonton. The townsite is accessible only by aircraft or by barge up the Athabasca river from Fort McMurray, Alberta, in summer. The general geographic setting of the Eldorado area is shown in Figure 1.

Travel from Eldorado to the thesis area was made possible by helicopter service provided by Eldorado Mining and Refining Company Limited. A field camp was set up on the north shore of Gibbs Lake, from which point it was possible to reach the thesis area on foot. The field work for the project was done in the period August 8 to 16, 1966.



II REGIONAL GEOLOGY AND GEOCHRONOLOGY

Regional Geology

The Lake Athabasca region is part of the Churchill Province of the Canadian Shield. The area is underlain by a sequence of regionally metamorphosed and granitized rocks, covered in places by a thin veneer of interbedded clastic sediments, volcanic flows and sills. A series of late dykes cut all rocks of the area. Table I shows the general stratigraphic sequence in the Lake Athabasca region as compiled by Trigg (1964). The rocks of the Tazin Group form a basement complex with younger Martin Formation rocks preserved in linear structural basins along the Black Bay and St. Louis faults and in the vicinity of Tazin Lake (Christie, 1953, p. 49). The basement complex has been intensely metamorphosed and displays complex fold patterns with a dominant northeasterly trend. Metamorphism reached the epidote-amphibolite facies over most of the area and locally attained the granulite facies. Christie (1953) noted a general increase in metamorphic grade from west to east which he attributed to a deeper level of erosion to the east.

The basement complex in the Lake Athabasca region can be divided into two structural environments (Beck, 1966, abstract):

- i. Linear belts consisting of a wide variety of rock types including meta-sedimentary rocks, meta-volcanic rocks, paragneiss, basic intrusive rocks and granites. The linear belts are characterised by isoclinal folding, intense faulting, brecciation and mylonitisation. The maximum metamorphic grade attained in the linear belts is the epidote-amphibolite facies although the grade is commonly lower.
- ii. Stable blocks consisting of subequal amounts of old basement granite, migmatites and paragneiss. These rocks are all strongly metamorphosed with some rocks in the granulite facies. In contrast with the linear belts, the stable blocks are relatively unaffected by faulting, although some uplift of the blocks may have occurred by faulting.

Table 1: Stratigraphic Succession - Lake Athabasca Area *

PRECAMBRIAN					
AGE	FORMATION	LITHOLOGY	THICKNESS	ABSOLUTE AGE	
Middle Proterozoic ?		Diabase dykes			
	I n t r u s i v e C o n t a c t				
	Athabasca Formation	Sandstone, minor shale, conglomerate	Unknown	400 m.y.	1670 m.y.
	U n c o n f o r m i t y				
Lower Proterozoic	Martin Formation	Conglomerate Basalt, andesite, flows and sills Arkose, sandstone, siltstone	8,000- 17,000'	1670 m.y.	2000 m.y.
	U n c o n f o r m i t y				
Proterozoic? or Archean?		Lamprophyre dykes Granite, granite gneiss		2000 m.y.	
	I n t r u s i v e C o n t a c t				
	Tazin Group	Mafic-rich rocks Conglomerate Dolomite, dolomitic quartzite Migmatites, paragneisses Quartzite, ferruginous quartzites	30,000'		

*after Trigg, 1964

Viking Lake Area

Viking Lake lies about 8 miles east of Eldorado, Saskatchewan. Geological maps of this region have been prepared by Christie, 1953; Blake, 1956: and Burwash, 1965. Figure 2 (enclosed in the map pocket at the end of this thesis) is a geological map of the Viking Lake area (redrawn after Burwash, 1965). This region is part of a linear belt along the St. Louis fault and is characterised by intense faulting with accompanying formation of mylonite. Topographic lineaments are common along the major fault zones. Escarpments are usually found along the smaller faults. There is a pronounced northeasterly fault trend in the area.

Mylonites are common in the vicinity of Viking Lake and indicate that intense brecciation accompanied the faulting. Many of the minor faults may post-date the period of mylonitisation as they appear to transgress mylonite zones.

The predominant rocks of the Viking Lake area are mafic and leucocratic gneisses. Lesser amounts of granite, amphibolite, pegmatite and dyke rocks are present.

Burwash (1965) described the mafic gneiss as a foliated or layered rock consisting of more than 15 per cent mafic minerals. The leucocratic gneiss is similar, but has less than 15 per cent mafic minerals. The gneisses are grey to pink weathering and show vaguely defined compositional banding on the weathered surface. The mineralogy of the gneisses is simple. Quartz, potash feldspar, plagioclase and hornblende or biotite (commonly altered to chlorite) form the major components. Zircon, apatite, sphene, pyrite and epidote are common accessory minerals. Blake (1956) interpreted the gneissic rocks north of Gibbs Lake as paragneiss with the compositional banding reflecting the original sedimentary composition.

The amphibolites of the Viking Lake area occur as elongate belts or pods. Most of these pods are only a few feet in width and a few tens or hundreds of feet in length. The typical amphibolite is dark green to black with a dark grey-brown

weathered surface. The amphibolites are composed of subequal amounts of hornblende and andesine with lesser amounts of quartz, biotite and occasional diopsidic pyroxene. Apatite, sphene, zircon and opaque minerals are common accessories (Burwash, 1965, p. 6-7, Blake, 1956, p. 20-22). Blake noted the occurrence of garnet in some amphibolite bodies. Chlorite and epidote are frequent secondary alteration products.

Granite occurs locally in the Viking Lake area. Burwash (1965) distinguished granite from leucocratic gneiss by the absence of a recognisable foliation on the weathered surface of the granite. Some of the rocks mapped as leucocratic gneiss could be granite with a secondary foliation imposed by dynamic metamorphism.

Two varieties of pegmatite are present in the Viking Lake area. Discordant microcline-muscovite pegmatites occur as late phases of the granite intrusions. These pegmatites are definitely later than some of the amphibolites, as pegmatite dykes can be seen cutting the amphibolites. Small discordant pegmatites occur at various places in the basement gneiss. Some of these pegmatites have been sheared and subjected to hematite and uranium mineralisation. Both sheared and fresh pegmatites are present in the thesis area.

The Viking Lake pegmatite has been dated by the K-Ar and U-Th-Pb methods (Lowdon, 1961, p. 19). This pegmatite is a sheared, hematized body.

Blake (1956) recognised quartz-monzonite, lamprophyre, and diabase or gabbro dykes in the Viking Lake area. Most of the dykes are only a few feet wide and have a near vertical dip. The dykes are younger than most of the regional structures, but Blake, (1956) suggests that some faulting may have occurred after the emplacement of the dykes.

The quartz monzonite rocks have a reddish-brown weathered surface on which iron stained feldspar phenocrysts stand out in rough alignment (Blake, 1956, p. 29). These rocks are variable in composition but typically contain 25-30 per cent quartz, 25-30 per cent microcline, 5-15 per cent biotite and about 35 per cent plagioclase (An_{30-33}).

The lamprophyre dykes have a chocolate brown weathered surface on which phenocrysts of biotite and potash feldspar stand out (Blake, 1956, p. 30-31). Grain size in these rocks is variable depending on the width of the dyke and the distance of the sample from the contact. Composition of the lamprophyres ranges from 30-50 per cent potash feldspar, 10-20 per cent biotite, 10-20 per cent hornblende, 5-15 per cent quartz and up to 10 per cent plagioclase. The composition of the plagioclase was not determined because of intense alteration. Diopside occurs in some specimens. Apatite and magnetite are common accessories. Some calcite-filled cavities are present.

Burwash (1965) noted that some of the dykes mapped by Blake as lamprophyre are porphyritic quartz monzonite. Burwash retained the term lamprophyre as a field name.

Diabase or gabbro dykes are common in the vicinity of Viking Lake (Burwash, 1965, p. 12-13). These dykes have a brown weathered surface on which small feldspar laths stand out. The diabase is composed of poorly twinned, zoned plagioclase feldspar laths ranging in composition from An_{40-60} , set in a finer grained ground mass of chlorite after pyroxene and hornblende. Minor amounts of potash feldspar and quartz are common. Small patches of calcite are present.

Geochronology

Geochronological studies in the Lake Athabasca region have been made by a number of investigators using several methods.

The first detailed study in the area was made by Robinson (1955) who studied the age relationships of the uranium deposits in the Beaverlodge area. From the isotopic composition of the uranium, thorium and lead in these deposits, Robinson calculated the age of the deposits and deduced that three distinct periods of mineralization had occurred at 1400-1600 m.y., 850-950 m.y. and 230-340 m.y. Most of his dates, however, are discordant (Robinson, 1955, p. 83 and 86) and should be reassessed on the basis of a concordia plot.

Russell and Farquhar (1960) dated a number of samples of uranium ore from the Ace Mine, Eldorado, and obtained discordant dates. The individual dates of the samples range from 590 to 1790 m.y. Russell and Farquhar recalculated the results using a concordia plot and obtained an intersection age for the mineralization of 1800 m.y. Lowdon (1960) reports the results of K-Ar and U-Th-Pb dating of the Viking Lake pegmatite. Concordant ages of 2015 and 2000 m.y. were obtained(?)

Beck (1966) investigated the ages of the granite and associated pegmatite bodies in the vicinity of Lake Athabasca. Rubidium-strontium isochron plots for nine granite samples collected from different localities define two isochrons with dates of 1820 m.y. and 2200 m.y.* The older granites are confined to the stable block environment of the region and have a low (0.700) $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio. The younger granites are all from the linear belts and have a significantly higher $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio. Potassium-argon dates of minerals from the same samples range from 1720 to 2015 m.y.

A detailed geochronological study of the Precambrian shield of the northeast corner of Alberta has been undertaken at the University of Alberta. A combination of potassium-argon, rubidium-strontium and uranium-thorium-lead methods of dating has been applied in an attempt to elucidate the geological history of the area. While the investigation is not complete, the preliminary data suggest that three distinct events can be recognised. Uranium-thorium-lead dating of zircons gave diffusion dates of 2250 and 1900 m.y. (Baadsgaard and Godfrey, 1967). Rubidium-strontium isochron plots for basement gneiss samples gave dates of 2280 and 1920 m.y. with an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.711. More recent data on granite, basement gneiss, and amphibolite whole rock samples and potassium feldspar and biotite mineral separates from these rocks suggest that three events can be recognised at 2300, 1920, and

*All Rb-Sr dates reported in this thesis are based on a $1.47 \times 10^{-11} \text{ year}^{-1}$ decay constant for Rb^{87} .

1670 m.y. The 1670 m.y. isochron is defined by the granites and represents the youngest recognised event in the area (Baadsgaard, personal communication).

Potassium-argon dates of hornblende and mica separates from rocks of the same area indicate two events at 1740-1830 m.y. and \sim 1900 m.y. (Godfrey and Baadsgaard, 1962; Baadsgaard, Cumming, Folinsbee and Godfrey, 1964; Baadsgaard and Godfrey, 1967).

The range of dates obtained by radiometric dating of samples from the northeast corner of Alberta and from the Lake Athabasca area of Saskatchewan are essentially identical. The results suggest a similar geological history for this part of the Churchill Province of the Canadian Shield. Three metamorphic or igneous events can be recognised in this area. The 1670 m.y. granite intrusion in the northeast corner of Alberta has not been recognised in Saskatchewan.

III GEOLOGY, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE PEGMATITE-GNEISS COMPLEX

General Geology

The area selected for detailed study is part of a small horst cut off between two northerly trending faults. The area is bounded on both the east and west side by prominent escarpments. A narrow zone of brecciated rock is present along the eastern margin of the block. Figure 3 (in the map pocket) is a geological map of the area. It shows the general geological features of the area and all sample locations. The sample numbers used on the map refer to the samples described in the text.

Interbanded leucocratic and mafic gneisses are the predominant rocks (appendix 1, D, F, H, L, and Q). A prominent foliation trending North 10° East and dipping nearly vertical is conspicuous on the weathered surface of the gneiss. A number of small concordant amphibolite bands and boudins are found in the gneiss (Appendix 1, E, R). The amphibolite bands are discontinuous and can be traced only for short distances. Most of the amphibolites are massive but some exhibit thin banding of mafic and felsic minerals. There is no preferred orientation of hornblende in the hand specimen.

Two small discordant pegmatite bodies are present in the area (see geological map, Figure 3, Appendix 1, I, J, M, N, P). The northern pegmatite is composed predominantly of microcline, quartz, and plagioclase as well as lenses of biotite. What appears to be a faint yellow uranium bloom is present on some of the weathered biotite. This pegmatite appears to have formed in a dilatant zone in the gneisses and partially replaced some of the pre-existing rocks. The main pegmatite band is approximately 3 feet wide (see expanded cross-section on geological map). It has a sharp contact on the west side and a smeared gradational contact on the east (Appendix 1, M,

W). On the east is an 18 inch wide band of altered amphibolite in which the hornblende is partially altered to biotite and chlorite (Appendix 1, O). Next is a six inch pegmatite band in which partially absorbed amphibolite can be observed (Appendix 1, P). This grades into fresh amphibolite on the east and then into a seven inch band of leucocratic gneiss (Appendix 1, Q). On the east of the leucocratic gneiss is several feet of amphibolite.

The southern pegmatite body is composed almost entirely of coarse grained microcline perthite (Appendix 1, I, J). The pegmatite has been sheared and is strongly iron stained. The field relationships and the contacts in this vicinity are obscure because the pegmatite has been cut by a lamprophyre dyke. The pegmatite definitely pre-dates the dyke intrusion.

The lamprophyre dyke intrusions are localised along the fault zone on the eastern side of the block. The dyke rocks parallel the foliation in the gneiss with local discordance. The lamprophyre dyke rocks have a chocolate brown weathered surface on which phenocrysts of biotite and potash feldspar stand out. Grain size depends on the thickness of the dyke and the distance of the sample from the contact. The rocks contain 30-50 per cent potash feldspar, 10-20 per cent biotite, 5-15 per cent quartz, up to 10 per cent plagioclase, and minor hornblende and diopside. The plagioclase is largely untwinned and deeply weathered and has a composition of about An_{60-65} . Minor magnetite, apatite and calcite are present. The calcite may be secondary and filling cavities in original rock. Partial chloritization of the biotite has occurred.

Regional Metamorphic History

The significant indicators of metamorphic grade attained in the area are:

- i. Plagioclase composition
- ii. Presence of potash feldspar
- iii. Absence of primary muscovite

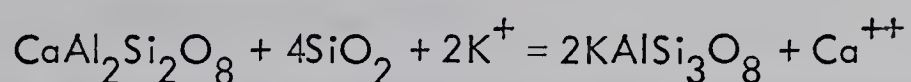
Winkler, 1965, defines the boundary of greenschist and the epidote-amphibolite facies on the change in plagioclase composition from $An \leq 7$ per cent in the greenschist facies to $An \geq 15$ per cent in the epidote-amphibolite facies. In these rocks the average plagioclase composition is An_{35} . The presence of microcline perthite and the absence of primary muscovite suggest that these rocks crystallised outside the muscovite stability field. The formation of microcline perthite is indicative of the sillimanite-almandine-orthoclase sub-facies of regional metamorphism (Winkler, p. 92-97). Winkler also suggests that 600-700° centigrade is a reasonable temperature range for the formation of this assemblage. Some anatectic melting is common under these temperature pressure conditions (Winkler, 1965, p. 96-97). The presence of well formed cross-hatched twinning in the microcline indicates that the feldspar crystallised as a monoclinic phase and inverted to a triclinic phase on cooling (Heier, 1957, p. 468). Heier also suggests that 500°C is a reasonable temperature of inversion. The ubiquitous presence of well twinned microcline perthite in this assemblage is indicative of high temperature of crystallisation.

In the present assemblage, the following retrograde metamorphic effects can be observed:

- i. The alteration of hornblende, biotite and garnet to chlorite.
- ii. Intense sericitization of plagioclase feldspar.
- iii. The formation of epidote at the expense of calcic-plagioclase.

The alteration of the hornblende, biotite and garnet probably result from mineral instability in the presence of decreasing temperature and/or pressure late in the metamorphic cycle. The sericitic alteration of the plagioclase and the formation of epidote from the calcic-plagioclase could result from deuteritic or hydrothermal alteration. There is no evidence for a time separation between the alteration of the mafic minerals and the plagioclase. These probably resulted from the same retrograde phenomena. The microcline in these rocks was only slightly altered during

the intense alteration of the plagioclase. This may be dependent upon kinetic factors (Hemley, Meyer, and Richter, 1961, p. 338-340). For this reason, most of the potassium feldspar in the gneisses is assumed to be primary. Some second generation microcline and quartz partially replace altered plagioclase (see Appendix 1, A, D, G, K, and P, also microphotographs 2, 3, 4, 5, 6, 7, 8). Orville (1962) suggests that potassium feldspar can form by the reaction:



However, some plagioclase feldspar in these rocks is completely altered to sericite without the formation of potassium feldspar. In other specimens, fresh or partially altered plagioclase has been replaced by microcline and quartz. These features indicate that some of the microcline and quartz has been introduced.

The pegmatitic rocks in the area are less altered than the surrounding gneisses. Fresh biotite and plagioclase are present in the pegmatite and absent elsewhere, specimen B66-29 being an exception. Thick biotite lenses in which interstitial minerals are almost completely absent occur in the coarse grained pegmatite. This biotite is only partially chloritized. The partial chloritization of the pegmatitic biotite and the absence of biotite in the gneiss indicate that the pegmatitic biotite is primary and was formed late in the metamorphic cycle after most of the alteration in the pre-existing rocks was completed. It is probable that the introduction of the microcline and quartz into the gneisses occurred at the same time as the formation of the pegmatite. The albite described in specimen B66-24 may have formed at the same time as the second generation microcline and quartz.

From the above discussion, the following sequence of events is indicated for this area:

- i. The formation of the paragneiss and metamorphism to the epidote-amphibolite facies.

- ii. Retrograde metamorphism and/or hydrothermal alteration during a period of decreasing temperature and/or pressure. A disequilibrium assemblage of greenschist and epidote-amphibolite facies minerals was formed.
- iii. Pegmatite formation.
- iv. Continuation of the retrograde metamorphism during which the biotite and plagioclase formed in phase iii are partially altered to chlorite and sericite.
- v. Faulting and brecciation.
- vi. Intrusion of the lamprophyre dykes. Minor alteration of biotite and plagioclase occurred after the intrusion of the dykes.

Geochemistry

Three total rock analyses and a number of partial analyses were made on selected samples. The analyses were made to determine whether any significant chemical differences existed between the gneisses and the pegmatite; and to establish a parentage for the amphibolites. The total rock analyses were made on two specimens of amphibolite and one specimen of gneiss. Partial analyses were made for potassium, sodium, calcium, chromium, nickel, and manganese on whole rock samples. Seven biotite and hornblende separates were analysed for sodium, potassium and cesium. The rubidium and strontium analyses made in the process of dating the rocks are included in the discussion. All analytical methods are described in Appendices 2 and 3. The analytical results are listed in Tables II to V below.

The origin of the amphibolites and the genetic relationships of the pegmatite and gneiss are different geochemical problems and will be discussed separately.

Amphibolites

The results of the total rock analyses of the amphibolites are similar to a number of representative analyses of basic igneous rocks (Turner and Verhoogen, 1962, p.

165-288). A wide variety of metamorphosed sedimentary rocks could also have this composition (Pettijohn, 1957, Chapter 8).

Evans and Leake (1960) summarize the average Cr, Ni and Sr content of basaltic rocks, shales, limestones and dolomites. The average Cr, Ni and Sr concentrations in basaltic rocks are 170, 130 and 465 part per million respectively. However, the respective concentrations of these elements can vary from 1 to 3000 ppm, 3 to 2000 ppm, and from 20 to 2000 ppm. The average K_2O/Na_2O , K/Rb and $Sr/Ca \times 10^3$ ratios for basaltic rocks are 0.41, 230, and 6.5 respectively (Heier and Adams, 1964, p. 276-297; Turekian and Kulp, 1956, p. 245). A similar wide range of trace element concentrations exists in sedimentary rocks. Cr, Ni and Sr concentrations can range from 1 to 200 ppm, 1 to 300 ppm, and from 10 to 8000 ppm, respectively. The alkali metal contents of sedimentary rocks are even more variable (see Heier and Adams, 1964, Table 20, p. 319-321).

The alkali metal contents of two amphibolites from the thesis area are included in Table III. The Cr, Ni and Sr concentrations of three amphibolites are included in Table IV. The K_2O/Na_2O and K/Rb ratios are close to the mean values for basaltic rocks. The Cr and Ni contents are less than the average values for basaltic rocks; the Sr content is close to the mean value for basaltic rocks. The $Sr/Ca \times 10^3$ ratio (5.3) is slightly less than the average ratio (6.5) in basaltic rocks. All of the trace and major element concentrations are within the range of concentrations in basaltic rocks and calcareous sedimentary rocks. For this reason, the chemical compositions do not indicate an origin for the amphibolites. The amphibolites could represent the metamorphosed equivalent of a wide variety of basic igneous rocks or metamorphosed calcareous sedimentary rocks.

Leake (1964) concluded that ortho-amphibolites cannot be distinguished from para-amphibolites by criteria based on chemical abundance. This conclusion applies to the amphibolites discussed above.

Table II: Total Rock Analyses

Component	Sample Number		
	<u>B66-47</u> ¹	<u>B66-26</u> ²	<u>B66-56</u> ³
SiO ₂	72.77	50.33	50.79
TiO ₂	0.22	1.27	1.82
Al ₂ O ₃	12.77	10.28	15.86
Fe ₂ O ₃	2.74	8.37	2.38
FeO	0.66	9.09	10.59
MnO	0.04	0.16	0.19
MgO	0.83	4.46	2.82
CaO	1.38	7.50	7.57
Na ₂ O	3.15	4.04	3.32
K ₂ O	4.82	1.58	2.06
P ₂ O ₅	0.07	0.29	0.47
H ₂ O ⁻	0.07	0.09	0.09
H ₂ O ⁺	0.73	1.73	1.53
Total	<u>100.25</u>	<u>99.19</u>	<u>99.49</u>

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Table III: Alkali Metal Content of Selected Whole Rock Specimens

Sample Number	Rock Type	% K ₂ O*	% Na ₂ O*	ppm Rb**	K ₂ O/Na ₂ O	K/Rb
B66-24	leucocratic gneiss	3.28	3.31	109	0.99	250
B66-26	amphibolite	1.61	4.15	52	0.39	257
B66-28	leucocratic gneiss	5.57	2.63	206	2.12	224
B66-48	leucocratic gneiss	3.84	3.31	132***	1.16	241
B66-49	microcline-rich pegmatite	7.56	1.79	244	0.87	257
B66-50	biotite-plagioclase pegmatite	2.45	4.26	144	0.58	141
B66-51	altered amphibolite	2.56	2.77	220	0.92	96
B66-52	biotite-microcline plagioclase pegmatite	1.79	3.97	119	0.45	125
B66-53	leucocratic gneiss	2.06	3.85	120	0.54	143
B66-54	amphibolite	1.92	3.04	71	0.63	224

* Determined by flame photometer

** Determined by isotope dilution

*** The rubidium in B66-48 was determined by x-ray fluorescence

Table IV: Alkali Metal Content of Biotite and Hornblende Separates

Sample No.	Sample Description	Per cent K_2O^*	Per cent Na_2O^{**}	ppm CS_2O^{**}
B66-48	Biotite, partially altered to chlorite	6.77	0.99	~ 43
B66-49	Biotite partially altered to chlorite	4.56	0.83	~ 43
B66-50	Biotite partially altered to chlorite	6.19	0.11	< 40
B-66-51	Hornblende and biotite partially altered to chlorite	5.96	0.26	~ 58
B66-52	Biotite partially altered to chlorite	6.04	0.78	< 40
B66-53	Biotite partially altered to chlorite	5.90	0.27	< 40
B66-54	Hornblende partially altered to biotite and chlorite	1.64	not measured	not measured

* Potassium analyses by precipitation with sodium tetraphenyl boron except for sample B66-49 which was analysed on the flame photometer

** Sodium and cesium analyses were made on flame photometer

Table V: Trace and Major Element Content of Selected Whole Rock Specimens

Sample Number	Rock Type	ppm Cr*	ppm Ni*	ppm Mn*	% Ca*	ppm Sr**	Sr/Ca x 10 ³
B66-22	leucocratic gneiss	10	23	221	1.36	-	
B66-23	microcline-rich pegmatite	20	15	129	1.98	-	
B66-24	leucocratic gneiss	22	-	458	2.30	246	10.7
B66-26	amphibolite	69	23	1455	9.64	498	5.2
B66-27	leucocratic gneiss	20	13	367	2.36	-	
B66-28	leucocratic gneiss	21	22	417	1.57	203	12.9
B66-48	leucocratic gneiss	21	9	355	2.91	207	7.1
B66-49	microcline-rich pegmatite	-	12	80	0.27	208	77
B66-50	biotite-plagioclase pegmatite	41	11	455	3.13	208	6.6
B66-51	altered amphibolite	39	13	1140	5.54	295	5.3
B66-52	microcline plagioclase	29	8	425	4.67	286	6.1
B66-53	leucocratic gneiss	54	-	484	4.30	322	7.5
B66-54	amphibolite	40	14	1441	9.79	541	5.5
B66-56	amphibolite	26	12	1398	8.41	-	-

* Determined by atomic absorption

** Determined by isotope dilution

Pegmatites and Gneisses

The results of the chemical analyses of the pegmatite and gneiss samples are summarized in Tables II to V. Additional Rb and Sr analyses are listed in Table VI.

The Cr and Ni concentrations in the pegmatite and gneiss samples are low. The Cr concentration ranges from less than 10 ppm to a maximum of 54 ppm in the gneisses, and from 0 to 120 ppm in the pegmatite. The range in Ni concentration is from 0 to 23 ppm in the gneiss and from 8 to 12 ppm in the pegmatite. The Mn concentrations in the pegmatite and gneiss reflect the mafic mineral content of the specimens. Manganese ranges from 129 to 458 ppm in the analysed samples. The Sr concentrations in both the pegmatite and gneiss are uniform and average 250 ppm, with no sample containing less than 200 ppm Sr. The Ca concentration varies from a low of 0.27 per cent in one of the pegmatite specimens to a maximum of 4.67 per cent in one of the gneisses. The $\text{Sr/Ca} \times 10^3$ ratios show more variation than is obvious from the individual results. The gneisses generally have a higher Sr/Ca ratio than the pegmatites. Sample B66-49 is an exception with a Sr/Ca ratio of 77.

The K, Na and Rb concentrations in the pegmatite and gneisses are variable. The $\text{K}_2\text{O/Na}_2\text{O}$ and K/Rb ratios show the trends better than the individual analyses. The $\text{K}_2\text{O/Na}_2\text{O}$ ratio ranges from 0.45 to 0.92 in the pegmatite and from 0.54 to 2.12 in the gneiss. The K/Rb ratios show the same trends as the $\text{K}_2\text{O/Na}_2\text{O}$ ratios. The K/Rb ratios in the pegmatite are significantly lower than in the gneiss. Pegmatite sample B66-49 is an exception to this trend.

Four biotite and biotite-hornblende separates from the pegmatite and gneiss were analysed for Na, K, and Cs. The Na content of the biotites ranges from 0.26 to 0.99 per cent; the K content of the same samples ranges from 4.56 per cent to 6.77 per cent. The hornblende sample contained 1.64 per cent K. The low K content of the biotites results from partial chloritization of the samples.

All of the biotites from the pegmatite gave positive responses for Cs on the flame photometer. Three of the samples contained measurable Cs. These samples contain between 40 and 60 ppm Cs_2O .

The above chemical data suggest that a small but significant chemical difference exists in the chemistry of the pegmatites and the gneisses. The K/Rb ratios may be used as an index of differentiation (Taylor, 1965, p. 144). K/Rb ratios between 150 and 300 are considered normal and ratios outside these limits indicate the concentration or depletion of Rb with respect to K (Taylor, p. 144). All of the pegmatite specimens have K/Rb ratios of less than 150. This indicates that some concentration of Rb with respect to K has occurred. The high K/Rb ratio of specimen B66-49 may be the result of concentration of Rb in the biotite lattice in preference to K-feldspar. Specimen B66-49 contains less biotite than adjacent specimens but is very rich in K-feldspar. The high Rb content of the sample is offset by the high K content of the K-feldspar.

The biotites from the pegmatite contain 40 to 60 ppm Cs_2O . The crustal abundance of Cs_2O is 2 to 3 ppm (Taylor, 1965, p. 148). From 18 to 29 ppm Cs_2O has been found in biotites from amphibolite facies gneisses (Heier and Adams, 1964, p. 308). On the basis of one analysis, the Cs_2O content of the biotite from the gneiss in this area is less than 40 ppm. This may indicate some concentration of Cs in the pegmatite.

The $\text{Sr}/\text{Ca} \times 10^3$ ratio in the gneisses ranges from 7.1 to 10.7. This is slightly higher than the $\text{Sr}/\text{Ca} \times 10^3$ ratios in the pegmatite. Turekian and Kulp (1956) list 16.3 to 23.0 as the range of $\text{Sr}/\text{Ca} \times 10^3$ ratios in granitic rocks. Sedimentary rocks have Sr/Ca ratios which are typically lower but which can vary over wide limits. The Cr and Ni concentrations in the gneisses and pegmatite are consistent with either an igneous or sedimentary parentage (Turekian and Carr, 1960, Table 2, p. 18). The Mn content in the pegmatite and gneiss reflects the percentage of

mafic minerals in the sample and has no genetic significance. The overall bulk chemistry of the gneisses is consistent with a meta-sedimentary origin. This conclusion agrees with that of Blake (1956) who described these rocks as paragneiss on the basis of field evidence.

The K_2O/Na_2O and K/Rb ratios are slightly lower in the pegmatite than they are in the gneiss. The Cs_2O concentration in the pegmatite is slightly higher than in the gneisses. These observations suggest that the alkali metals were concentrated in the hydrothermal or pegmatitic fluids before the emplacement of the pegmatite. The high Sr and Ca content of the pegmatite samples indicates that some absorption of the pre-existing material must have occurred. This conclusion is supported by the petrographic evidence described in the previous section. Isotopic evidence for an external origin of the pegmatitic fluids is discussed below.

Geochronology

Radiometric dating was utilized to help determine the metamorphic history and to date the rocks in the thesis area. Sixteen samples were selected for dating. All sixteen whole rock samples were dated by the rubidium-strontium method. Biotite and hornblende separates were prepared from the five pegmatite samples and from an amphibolite sample. The biotite and hornblende separates were dated by the potassium-argon method.

The theoretical basis on which the whole rock rubidium-strontium method is based and the results of the rubidium-strontium dating will be described first[†].

Rb^{87} decays to Sr^{87} by β -particle emission. If Rb_p^{87} is the number of Rb^{87} atoms in a phase at the present time, and λ is the rate of radioactive decay of Rb^{87} , it can be shown that $Rb_o^{87} = Rb_p^{87} e^{\lambda t}$, where Rb_o^{87} was the initial number of Rb^{87}

[†]This derivation of the isochron equation is modified after Hamilton (1965) p. 98-99.

atoms in the phase.

But, $Rb_{\text{o}}^{87} - Rb_{\text{p}}^{87} = Sr^{87*}$, where Sr^{87*} is the number of Sr^{87} atoms formed by radioactive decay.

$$Rb_{\text{p}}^{87}(e^{\lambda t} - 1) = Sr^{87*}$$

$$\text{and } Sr_{\text{p}}^{87} = Sr_{\text{o}}^{87} + Sr^{87*}$$

$$\text{By substitution: } Sr_{\text{p}}^{87} = Sr_{\text{o}}^{87} + Rb_{\text{p}}^{87}(e^{\lambda t} - 1)$$

When λ is large, $e^{\lambda t} - 1 \approx \lambda t$.

Using this substitution and dividing both sides of the resulting equation by Sr^{86} (invariant), the following equation is obtained:

$$(Sr^{87}/Sr^{86})_{\text{p}} = (Sr^{87}/Sr^{86})_{\text{o}} + (Rb^{87}/Sr^{86})_{\text{p}} \lambda t$$

This is the equation of a straight line of the form

$$y = ax + b$$

where $y = (Sr^{87}/Sr^{86})_{\text{p}}$, $x = (Rb^{87}/Sr^{86})_{\text{p}}$ and the slope of the line $a = \lambda t$. The y intercept is the initial $(Sr^{87}/Sr^{86})_{\text{o}}$ in the phase. A plot of $(Rb^{87}/Sr^{86})_{\text{p}}$ against $(Sr^{87}/Sr^{86})_{\text{p}}$ is called an isochron plot. The slope of the line is proportional to the time elapsed since the system became closed with respect to Rb and Sr. The method requires that all samples are coeval and have the same $(Sr^{87}/Sr^{86})_{\text{o}}$.

The method of sample preparation and the methods of measurement are described in appendix 4. An isochron plot of Rb^{87}/Sr^{86} versus Sr^{87}/Sr^{86} is shown in figure 4. The unspiked (Sr^{87}/Sr^{86}) ratios are independent of uncertainty in the composition of the Sr spike. The unspiked (Sr^{87}/Sr^{86}) ratios are considered more accurate and were used to plot the isochron.

The points on the isochron plot fall into two distinct sets on the basis of rock type. Four of the pegmatite samples and the two amphibolite samples fall on a line. The seven gneiss samples and one pegmatite sample define a second line. There is considerable scatter of the points about the lines. The isochron for the gneisses includes points with a Sr^{87}/Sr^{86} scatter of ± 0.004 from the line. The isochron for the pegmatite has less scatter as all points are within ± 0.002 of the line.

Table VI: Rubidium, Strontium Data for Whole Rock Isochrons

Sample Number	Sample Description	Common Sr ppm	Total Rb ppm	$\frac{^{87}\text{Sr}}{^{87}\text{Sr} + \text{N}}$	$\frac{\text{Rb}}{\text{Sr}}$	$\frac{^{87}\text{Sr}}{^{87}\text{Sr} + \text{spiked sample}}$	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ unspiked sample
B66-15	brecciated melanocratic gneiss	236.3	89.9	0.075	1.10	.746	.746
B66-19	brecciated melanocratic gneiss	202.2	252.3	0.115	3.61	.793	.793
B66-20	brecciated melanocratic gneiss	227.1	176.6	0.083	2.252	.770	.776
B66-24	leucocratic gneiss	245.9	109.1	0.060	1.28	.762	.755
B66-26	amphibolite	498.1	52.2	0.017	0.302	.713	.712
B66-28	leucocratic gneiss	203.3	205.7	0.121	2.93	.798	.798
B66-29	leucocratic gneiss	206.8	154.5	0.108	2.16	.786	.788
B66-32	leucocratic gneiss	343.6	150.6	0.512	1.27	.753	.747
B66-34	iron stained microcline rich pegmatite	247.0	192.8	0.431	2.26	.775	.766
B66-38	iron stained microcline rich pegmatite	238.2	225.2	0.097	2.73	.780	.781
B66-43	leucocratic gneiss	419.1	148.2	0.041	1.02	.741	.744
B66-44	leucocratic gneiss	225.4	167.3	0.080	2.15	.767	.773
B66-49	microcline-rich pegmatite	208.1	243.7	0.125	3.39	.814	.801
B66-50	biotite-plagioclase pegmatite	294.6	143.6	0.057	1.42	.751	.752
B66-52	microcline-plagioclase pegmatite	285.7	119.0	0.053	1.23	.747	.742
B66-53	leucocratic gneiss	321.5	120.4	0.295	1.08		.748
B66-54	amphibolite	540.9	71.2	0.015	.381	.722	.722

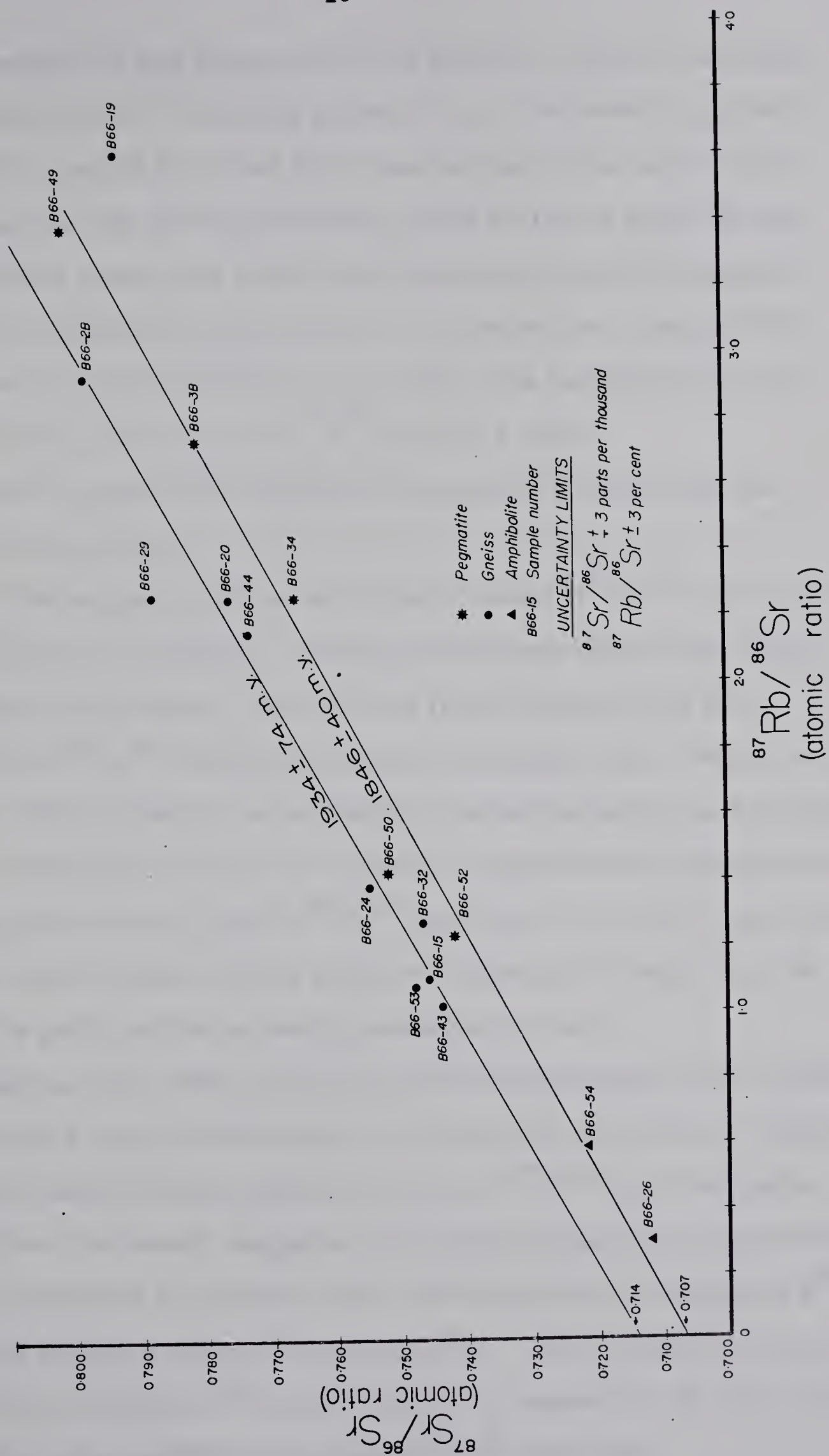


FIGURE 4. Rb-Sr isochrons for the gneisses, pegmatite and amphibolites

Straight lines were fitted to each set of points by a method of least squares which assumes that the X-coordinate is without error. (The method is described in Appendix 5). Samples B66-19 and B66-29 were omitted from the isochron for the gneisses because these points are completely outside the limit of scatter (± 0.004). The two amphibolite samples were omitted from the pegmatite isochron for geological reasons. On the basis of the least squares fit, the gneisses have an age of 1934 ± 74 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.714 ± 0.002 . The pegmatites have an age of 1846 ± 40 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.707 ± 0.002 .

Several reasons can be suggested for the scatter of the points about the isochron for the gneisses.

i. The paragneiss bands did not achieve a common $\text{Sr}^{87}/\text{Sr}^{86}$ at the time of the initial high grade metamorphism. This reason is discounted because other investigators (Pidgeon and Compston, 1965; Purdy and York, 1966) have found that a homogeneous $\text{Sr}^{87}/\text{Sr}^{86}$ is attained in high grade metamorphic rocks. Pidgeon and Compston (1965) studied the age relationships of banded paragneiss around the Cooma granite. Their results indicate that the granite, the migmatite zone and cordierite-orthoclase zones have very similar $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios. From this, Pidgeon and Compston infer that almost complete mixing and exchange of Sr isotopes occurred between the granite and the surrounding metasedimentary rocks.

Purdy and York (1966) collected granite and gneiss samples along a 125 mile traverse across a high grade metamorphic terrane near Red Lake, Ontario. There was no reason to assume that these samples had the same $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio before metamorphism. The isotopic composition of the sample was determined and good colinearity of points was obtained on an isochron plot. This indicated that a homogeneous $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio had been achieved during metamorphism. Purdy and York note that the small amount of radiogenic Sr^{87} present at the time of metamorphism (2.45 b.y. ago) would minimize the possibility of a variable $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio.

ii. Leaching of weakly held Sr^{87} from the mineral lattices has occurred.

A depletion of Sr with respect to Rb can take place during weathering. Rb occurs in the inter-layer cationic positions in the clay minerals and micas (Whiteney and Hurley, 1964, p. 430-431). Radiogenic Sr^{87} which is formed from Rb atoms in these positions is more loosely held and may be lost by solution (Whitney and Hurley). Loss of radiogenic Sr^{87} could be the cause of the anomalous values of specimen B66-19. This specimen is a brecciated gneiss which was collected near a fault zone and could have lost radiogenic Sr at the time of faulting.

iii. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of some gneiss bands was altered by metasomatic activity at the time of the pegmatite formation. Homogenization of the $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratio was not achieved after this event. The metasomatic activity would alter the more permeable bands in the gneiss to a greater extent than it would alter the competent or impermeable bands. If the metasomatic fluids had a different $\text{Sr}^{87}/\text{Sr}^{86}$ than the rocks which the fluids were permeating, incomplete homogenization would result in a different $\text{Sr}^{87}/\text{Sr}^{86}$ in the various bands. If subsequent homogenization of the Sr isotopes occurred, complete overprinting of the old isochron would be expected. Partial overprinting would only increase the scatter of the points.

iv. The scatter of points represents analytical error in measurement of the isotope ratios. The measurement error contributes very little to the scatter of the points. The reproducibility of measurement on duplicate runs of the same sample is better than ± 3 parts per thousand for $\text{Sr}^{87}/\text{Sr}^{86}$ and within ± 3 per cent for $\text{Rb}^{87}/\text{Sr}^{86}$. The scatter of the points is outside this range.

v. The scatter of the points results from analytical errors in sampling. The whole rock samples were prepared by crushing about one pound of rock, first in a jaw mill, then in a rotary crusher. The sample from the rotary crusher were split 3 to 1 and the smaller split fractions were crushed to a fine powder in a rotary blending mill. These samples were considered homogeneous and were used to prepare the Rb and Sr

samples. Some variation in grain size is present in these samples. This could result in inhomogeneous samples being selected for the different analyses. Five of the sixteen samples analysed for Sr have $\text{Sr}^{87}/\text{Sr}^{86}$ spiked and unspiked ratios which differ by greater than ± 0.003 . Part of this difference may result from sampling error.

The author feels that partial overprinting of the older isochron during the period of metasomatic activity may have been the most significant cause of the scatter of points about the gneiss isochron. It is unlikely that leaching of radiogenic Sr was significant except for specimen B66-19.

Four samples of pegmatite define an isochron with an age of 1846 ± 40 m.y. and an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.707 ± 0.002 . The results for the pegmatite samples show less scatter than the points for the gneiss samples. "Pegmatite" sample B66-50 is an exception to this pattern as it falls on the isochron for the gneisses. A thin section of B66-50 shows that it is composed predominantly of strongly altered plagioclase. There is less than 1 per cent microcline in the specimen. It is probable that incomplete replacement of the pre-existing plagioclase has occurred and overprinting of the old age was not complete. For this reason, the sample was included in the calculation of the older isochron.

The results for the two amphibolite specimens lie very close to the pegmatite isochron. These points were not used in the calculation of the isochron because there is no geological evidence to suggest that the formation of the pegmatites and amphibolites was coeval. One amphibolite has been partially replaced by pegmatite and is definitely older than the pegmatite.

The initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ in the pegmatite and gneisses are significantly different.

The controlling factors of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio in sedimentary materials are provenance, environment of deposition, and grain size of the particles. Chemical

sediments would reflect the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the environment of deposition. Clastic sediments contain Sr in the mineral phases. This Sr would have the same isotopic composition as the source rock. With weathering and transportation some Sr would be leached from the particles and lost into the exogenic cycle. Fine grained clastic sediments can become depleted in Sr with respect to Rb. Fixation of Rb with K occurs in the interlayer cationic positions in the clay minerals and micas. Sr remains in solution (Whitney and Hurley, 1964, p. 430-431). If the sedimentary rocks become metamorphosed and the $\text{Sr}^{87}/\text{Sr}^{86}$ ratios homogenize, a higher $\text{Sr}^{87}/\text{Sr}^{86}$ ratio results because of the inherited radiogenic Sr^{87} . The high initial $\text{Sr}^{87}/\text{Sr}^{86}$ in the gneisses could have been attained in this manner. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ is consistent with a sedimentary derivation from an older terrane.

The amphibolites may be the metamorphosed equivalent of a chemical sediment with minor admixed clastic material. The $\text{Sr}^{87}/\text{Sr}^{86}$ in chemical sediments would probably homogenize to the $\text{Sr}^{87}/\text{Sr}^{86}$ in the environment of deposition. The $\text{Sr}^{87}/\text{Sr}^{86}$ in precambrian seas may have been as low as 0.7004 but was probably higher (see discussion in Hamilton, 1965, p. 111-112). Thus the calcareous sediments may have equilibrated to a different $\text{Sr}^{87}/\text{Sr}^{86}$ than the clastic sediments in the same environment. The later metamorphism may not have homogenized the $\text{Sr}^{87}/\text{Sr}^{86}$ in the calcareous metasedimentary rocks to the same $\text{Sr}^{87}/\text{Sr}^{86}$ as was attained in the clastic metasedimentary rocks. Although such an hypothesis explains the anomalous data for the amphibolites, it must remain tentative as the amphibolites have not been shown by other evidence to be metasedimentary in origin or to have formed at the same time as the gneisses.

The pegmatite clearly postdates the gneisses and appears to have partially replaced part of the pre-existing rocks at the time of formation. Heier (1964) has suggested that anatectic melting of K-rich minerals which contain a high concentration of Rb⁸⁷ and radiogenic Sr^{87} would lead to a higher $\text{Sr}^{87}/\text{Sr}^{86}$ in the early melting

phase and a lower $\text{Sr}^{87}/\text{Sr}^{86}$ in the residue if isotopic exchange does not occur between the two phases. A process which would lead to the reverse situation has not been suggested. If the pegmatitic fluids had formed by anatectic melting of the gneiss, a higher $\text{Sr}^{87}/\text{Sr}^{86}$ would have been expected. The lower $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the pegmatite likely indicates a partial external source for the pegmatitic material. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the pegmatite is probably a composite of low initial ratio material with some higher initial ratio material from the gneiss. Incomplete homogenization of the materials probably causes the scatter of the points on the isochron.

A partial external source for the pegmatitic material is consistent with the chemical evidence discussed previously.

Six potassium-argon dates were made on biotite and hornblende separates (the theoretical basis for K-Ar dating is described in Hamilton, 1965, p. 47-79). Four of the samples were biotite separates from the pegmatite, one sample was a biotite separate with hornblende contaminant from an amphibolite body which had been partially replaced by the pegmatite. The sixth sample was a hornblende separate from an amphibolite. All of the biotite and hornblende samples were partially altered to chlorite.

The method of the extraction of the Ar, the measurement of the isotopic ratios and the calculation of the radiometric date of the sample has been described by Goldich et al (1961). The K was extracted by a modified Abbey leach method and precipitated as potassium tetraphenylboron (see Appendix 2). No correction was made for Rb which co-precipitates with K. No replicate analyses were made for K or Ar. However, previous analyses made at the University of Alberta laboratory on the United States Geological Survey standard muscovite (reported by Lanphere and Dalrymple, 1965, p. 3500-3501) indicates that the analytical errors in the method are less than 3 per cent. The radiometric ages range from 1619 to 1892 m.y. This is a greater range of variation than can be accounted for by analytic errors.

Table VII: Potassium-Argon Dates

Sample No.	Description	K^{40} , ppm	Ar^{40} , ppm	Date $\times 10^6$ years
B66-48	Biotite, partially altered to chlorite	6.90	1.1738	1746
B66-50	Biotite, partially altered to chlorite	6.20	1.1680	1863
B66-51	Biotite and hornblende, partially altered to chlorite	5.97	0.9063	1619
B66-52	Biotite, partially altered to chlorite	6.05	1.1682	1892
B66-53	Biotite, partially altered to chlorite	5.91	1.002	1742
B66-54	Hornblende, partially altered to chlorite	1.64	0.2659	1690

The wide variation in age of such a limited area indicates that the minerals have not remained a closed system since the time of formation. The two mineral separates which contain hornblende have lower ages than the biotite separates. This indicates that the hornblendes have lost part of the radiogenic Ar. This pattern is opposite to the results obtained by Hart (1961) who concluded that hornblende retains Ar as well as or better than biotite.

If the 1892 m.y. date is accepted as the minimum age of the pegmatite, the younger ages have been updated after the formation of the pegmatite. The updating does not appear to be related to the known geological events in the area. It is unlikely that the dates can be related to the post-pegmatite faulting. The pegmatite samples are not brecciated nor are any of the rocks in the immediate vicinity of the pegmatite brecciated. Also, there is no systematic decrease in the age of the samples toward the fault zone. The lamprophyre dyke intrusions which appear to post-date the faulting are small and are not in contact with the pegmatite. The younger samples in the group are not the samples nearest to the dyke. For this reason, the effect of the dyke intrusion is considered negligible.

The fractional loss of Ar^{40} from biotite by weathering is substantially greater than the fractional loss of K (Goldich and Gast, 1966, p. 372-375). This may result in significant lowering of the K-Ar date. The biotites in the pegmatite do not appear weathered although alteration to chlorite is ubiquitous and the K contents of the biotites are lower than in fresh biotites. It is possible that some K and Ar have been lost from the lattice by weathering. This may have contributed to the anomalous dates.

There is no evidence for geological events to account for the variation in the K-Ar dates. The difference in the individual dates cannot be attributed to different rates of cooling or to different temperature-pressure environments because the samples are so close together (see expanded cross-section on Figure 3) it is unlikely that a significant temperature or pressure gradient could exist between

them. The individual dates may be related to the degree of alteration of the minerals which were dated but there is no evidence to support this hypothesis. If the $1.39 \times 10^{-11} \text{ year}^{-1}$ decay constant for Rb^{87} is used, the pegmatite date is 1947 m.y. which is older than the oldest K-Ar date. The younger K-Ar dates may be attributed to Ar loss during the period of metamorphism which followed the formation of the pegmatite. However, the limited data available for the thesis area do not provide any justification for the selection of one decay constant in preference to the other.

The author accepts the Rb-Sr date as the most reasonable time for the formation of the pegmatite because the Rb-Sr dating was done on whole rock specimens which are less susceptible to weathering alteration and metamorphic overprinting than K-Ar dates on mineral separates. The discordant K-Ar dates are attributed to the metamorphic activity which followed the formation of the pegmatite.

IV SUMMARY AND CONCLUSIONS

The thesis area is part of a larger, intensely deformed belt along the major St. Louis fault. The rocks are leucocratic and mafic gneisses containing a number of small concordant amphibolite pods and stringers. There are two small discordant pegmatite bodies in the area.

The regional metamorphic history of this part of the Churchill Province is complex. This complexity is reflected on a local scale in the thesis area. The maximum metamorphic grade attained was the sillimanite-orthoclase subfacies in which the temperature and pressure were sufficient to re-crystallize potassium feldspar. Retrograde metamorphism under conditions of falling temperature and/or pressure caused intense sericitic alteration of the plagioclase feldspar, the alteration of the mafic minerals to chlorite and the formation of epidote from calcic-plagioclase. Metasomatic activity began late in the metamorphic cycle after the alteration of the plagioclase and mafic minerals was essentially complete. Partial replacement of the altered plagioclase by microcline occurred. Some introduction of quartz and albite accompanied the second generation microcline.

The two pegmatite bodies formed after the initial retrograde metamorphic alteration was essentially complete. The pegmatites probably formed in dilatant zones by partial replacement of pre-existing material during the same period of metasomatic activity that saw the introduction of secondary microcline, quartz and albite into the gneisses. Some metamorphic activity continued after the formation of the pegmatite because the pegmatitic biotite is partially altered to chlorite and the plagioclase feldspars are partially sericitized.

A limited chemical study of the rocks in the area was only partially successful. The Cr, Ni, Sr, Rb, Ca, Na, K, and Mn content of the amphibolite bodies was found to be compatible with either a sedimentary or an igneous derivation

and no genetic interpretations could be made from the results. The chemical results for the same elements in the gneisses and pegmatite were only slightly more significant. The chemical composition of the gneisses was shown to be compatible with a sedimentary origin, although insufficient data was available to show this result indisputably. Differential concentration of the alkali metals was found in the pegmatite. The K/Rb ratios in the pegmatite are less than the normal crustal ratios. The Cs concentration in the pegmatitic biotites is slightly enriched over the normal crustal abundance of Cs in biotites from similar environments. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio in the pegmatite is 0.707 ± 0.002 . This is lower than the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio in the gneisses (0.714 ± 0.002) and indicates that the pegmatite could not have been derived by anatectic melting of the gneisses. The high concentrations of Sr and Ca in the pegmatite show that some contamination of the pegmatitic material occurred at the time of emplacement. This contamination resulted from partial replacement of the pre-existing rocks. The $\text{Sr}^{87}/\text{Sr}^{86}$ ratio in the pegmatite is a composite ratio derived by mixing of the contaminant material and the pegmatite material.

Radiometric dating by the Rb-Sr isochron method gave a metamorphic date of 1934 ± 74 m.y. for the gneisses. Four samples of pegmatite give an isochron with a date of 1846 ± 40 m.y. This date probably represents the time of formation of the pegmatite as the post-pegmatite metamorphic alteration is very weak. The scatter of the points about the line for the gneisses probably results from an inhomogeneous $\text{Sr}^{87}/\text{Sr}^{86}$ initial ratios in the different gneissic bands. This inhomogeneity may have been caused by the addition of material with a different $\text{Sr}^{87}/\text{Sr}^{86}$ ratio to some of the gneissic bands at the time of the pegmatite formation. The points on the pegmatite isochron are less scattered than the points about the gneiss isochron. The limited scatter of these points may also have resulted from incomplete homogenization of the $\text{Sr}^{87}/\text{Sr}^{86}$ ratios in portions of the pegmatite which absorbed older material.

The two amphibolite points lie on the isochron for the pegmatite. These points were not included in the calculation of the line because geological evidence indicates that the amphibolites may be older than the pegmatite.

Six K-Ar dates were made on biotite and hornblende separates from the pegmatite and from an amphibolite. These dates range from 1619 to 1892 m.y. The two specimens containing hornblende gave dates of 1619 and 1692 m.y. The biotite dates range from 1742 to 1892 m.y. This spread of dates indicates that some of the samples lost radiogenic Ar. There is no evidence in the area for a local event which would account for the Ar loss. The anomalous dates may result from resetting of the K-Ar clocks during the weak metamorphic event which followed the emplacement of the pegmatite and chloritized the mafic minerals. The individual dates may be related to the degree of alteration of the minerals although no data is available to substantiate or refute this possibility.

The author accepts the Rb-Sr date of the pegmatite as the most reasonable because the whole rock date is less susceptible to weathering alteration and metamorphic overprinting. If the $1.39 \times 10^{-11} \text{ year}^{-1}$ decay constant for Rb^{87} is used, the whole rock pegmatite date is 1947 m.y., which is older than the oldest K-Ar date.

The author considers that the pegmatite and gneiss whole rock isochrons represent different geological events although the error limits of the two isochrons overlap. The ages are considered significant because the time of metamorphism of the gneisses was shown by petrographic evidence to pre-date the time of formation of the pegmatite. Also, both 1900 and 1800 m.y. events have been found in the area by other workers.

All of the radiometric dates obtained in the current investigation fall within the age range of the Hudsonian orogeny in the Churchill Province of the Canadian Shield (Wanless et al, 1966).

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APPENDIX I

PETROGRAPHIC METHODS AND DESCRIPTIONS

Thin sections were cut from most of the samples which were dated. These were examined with a petrographic microscope and are described below. The descriptive terminology is taken from Moorhouse (1959, p. 159-161 and 399-410). The term leucocratic and mafic are used by the author to differentiate between specimens containing less and greater than 15 per cent mafic minerals respectively. The plagioclase compositions were determined on sections cut normal to 010 as described by Kerr (1959) p. 257-259. A universal stage was used to orient the thin section so that the zone was exactly normal to 010. The mineral percentages in the rocks were determined by point counting along traverses two mm. apart. A minimum of 500 points was counted for each specimen. Inhomogeneity of the specimens and parallel orientation of the platy minerals limit the accuracy of the method. The essential mineral percentages are considered within ± 5 per cent. The accessory mineral percentages may be too high.

A. B66-15 Brecciated mafic gneiss

This rock is dark grey to black on the fresh surface and has a reddish brown weathered surface. It is fine to medium grained with numerous prophyroblasts of quartz and microcline. The rock is foliated but does not have well defined compositional banding. The specimen consists of altered plagioclase ($Ab_{31}An_{69}$) 15 per cent, sericitic alteration products after plagioclase, 21 per cent, quartz 23 per cent, microcline perthite 8 per cent, chloritic alteration products, 31 per cent, accessory minerals including garnet, apatite, zircon, pyrite, calcite, graphite and epidote 2 per cent. The microcline and quartz have poikiloblastic textures and occur as interstitial blebs veining the plagioclase. Some myrmekite

is present. The development of myrmekite and the interstitial microcline and quartz suggest incipient replacement of the plagioclase by microcline and quartz. The development of the microcline preceded the faulting in the area as some of the microcline is brecciated.

Microphotograph 1 shows the garnet to chlorite alteration.

B. B66-19 Brecciated mafic gneiss

similar to specimen B66-15

C. B66-20 Brecciated mafic gneiss

similar to specimen B66-15

D. B66-24 Leucocratic gneiss

This rock is reddish brown on both fresh and weathered surfaces. Foliation and compositional banding appear to be well developed in the hand specimen but are less distinct in the thin section. Grain size is variable. Most of the rock is fine to medium grained by porphyroblasts of microcline and quartz up to 1.5 cm. diameter are present. The specimen contains plagioclase ($\text{Ab}_{88}\text{An}_{12}$) 8 per cent, sericitic alteration products after plagioclase 40 per cent, microcline perthite, 8 per cent, quartz 34 per cent, chloritic alteration products 9 per cent, accessory minerals including calcite, apatite and zircon 1 per cent. There appear to be two generations of plagioclase in the rock: the primary plagioclase is almost completely altered to sericite, the secondary plagioclase is still fresh. Interstitial blebs of microcline and quartz are present in the primary plagioclase and suggest incipient replacement. The albite probably developed at the same time as the microcline and quartz. (See microphotographs 2 and 3).

E. B66-26 Amphibolite

This rock has a dark greenish black fresh surface and a light grey weathered surface. The specimen is medium grained with a massive equigranular texture. Some dimensional orientation of the amphibole is present. The specimen contains plagioclase ($\text{Ab}_{35}\text{An}_{65}$) 23 per cent, sericitic alteration products after plagioclase 23 per cent, hornblende 31 per cent, quartz 2 per cent, chloritic alteration products after hornblende 18 per cent, accessory minerals including apatite, sphene, pyrite and zircon 3 per cent. Small veinlets of epidote and K-feldspar are present in the hand specimen.

F. B66-28 Leucocratic gneiss

similar to specimen B66-24

G. B66-29 Leucocratic gneiss

This rock is fine to medium grained with a light grey color. Compositional banding is distinct in the hand specimen. The rock is composed of plagioclase ($\text{Ab}_{35}\text{An}_{65}$) 22 per cent, sericitic alteration products after plagioclase, 2 per cent, quartz 54 per cent, microcline perthite 10 per cent, biotite, 9 per cent, chloritic alteration products after biotite 3 per cent, accessory minerals including zircon and apatite, less than 1 per cent. The plagioclase feldspar in the specimen is comparatively fresh. Some myrmekite is present (see microphotograph 4). Small blebs of microcline and quartz occur within the plagioclase.

H. B66-32 Leucocratic gneiss

This specimen is similar to specimen B66-29 except that hornblende is present instead of biotite.

I. B66-34 Iron Stained Microcline-rich pegmatite

similar to specimen B66-38

J. B66-38 Iron Stained Microcline-rich pegmatite

This specimen is composed predominantly of coarse grained microcline perthite with lesser amounts of quartz and extremely altered plagioclase. The entire specimen is iron stained and has a deep reddish-brown color on both fresh and weathered surfaces.

K. B66-43 Leucocratic gneiss

This specimen is reddish brown in color. The rock is fine to medium grained with quartz and microcline porphyroblasts up to 0.5 cm in diameter. The composition is: Plagioclase ($\text{Ab}_{38}\text{An}_{64}$) 5 per cent, sericitic alteration products after plagioclase 52 per cent, microcline perthite 21 per cent, quartz 8 per cent, chloritic alteration products 13 per cent, accessory minerals including apatite, pyrite, sphene, zircon and hematite 1 per cent. Poikiloblastic intergrowths of quartz and microcline in the altered plagioclase and fine grained fresh plagioclase are indicative of metasomatic activity and the incipient replacement of the altered plagioclase.

L. B66-44 Leucocratic gneiss

similar to specimen B66-43

M. B66-49 Microcline-rich pegmatite

This specimen is very coarse grained. It is composed predominantly of microcline perthite with subordinate amounts of quartz, albite and biotite. The plagioclase is extremely altered and has been replaced in part by microcline and quartz (see microphotographs 5 and 6). The biotite is partially altered to chlorite.

N. B66-50 Biotite-Plagioclase pegmatite

This specimen is very coarse grained. It is composed of partially altered plagioclase ($\text{Ab}_{70}\text{An}_{30}$) 45 per cent, sericitic alteration products after plagioclase 25 per cent, quartz 10 per cent, biotite 10 per cent, chloritic alteration products after biotite 10 per cent, microcline less than 1 per cent (see microphotograph no. 8).

O. B66-51 Altered amphibolite

This specimen is similar in color, grain size and texture to specimen B66-26. It is composed of plagioclase ($\text{Ab}_{36}\text{An}_{64}$) 37 per cent, sericitic alteration products after plagioclase 1 per cent, biotite 31 per cent, hornblende 21 per cent, chloritic alteration products after biotite and hornblende 7 per cent, accessory minerals including zircon, apatite, sphene and pyrite 3 per cent.

P. B66-52 Microcline-plagioclase pegmatite

This specimen is similar to B66-49 in grain size and texture. It is composed of equal amounts of microcline perthite, quartz and albite. The plagioclase is partially altered to sericite. Some of the plagioclase is veined and partially replaced by microcline (see microphotograph number 8).

Q. B66-53 Leucocratic gneiss

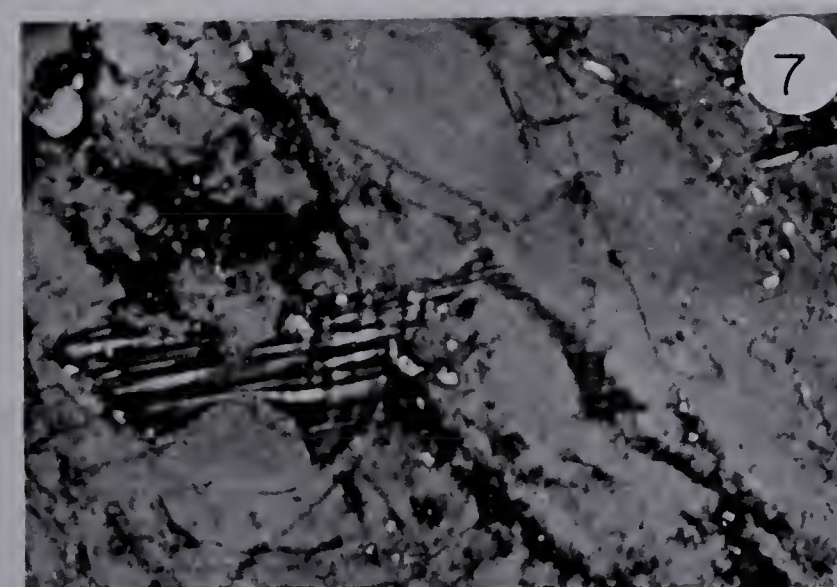
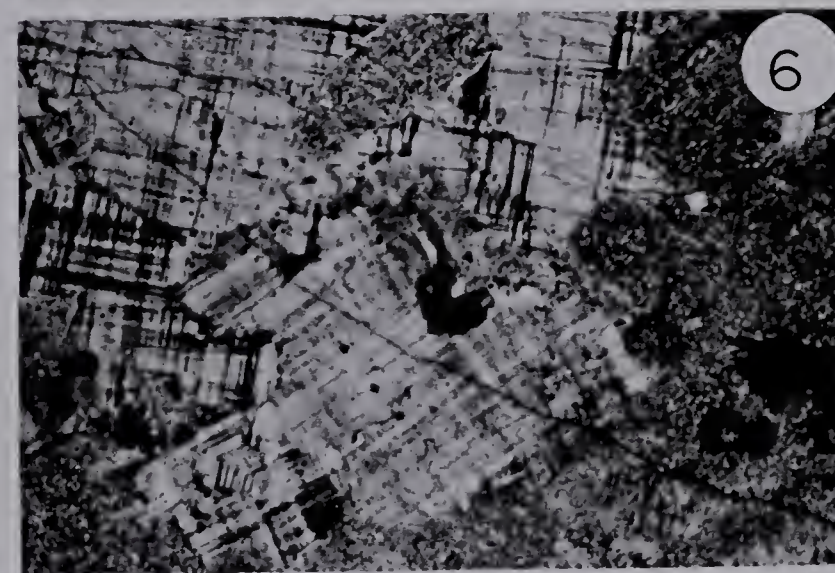
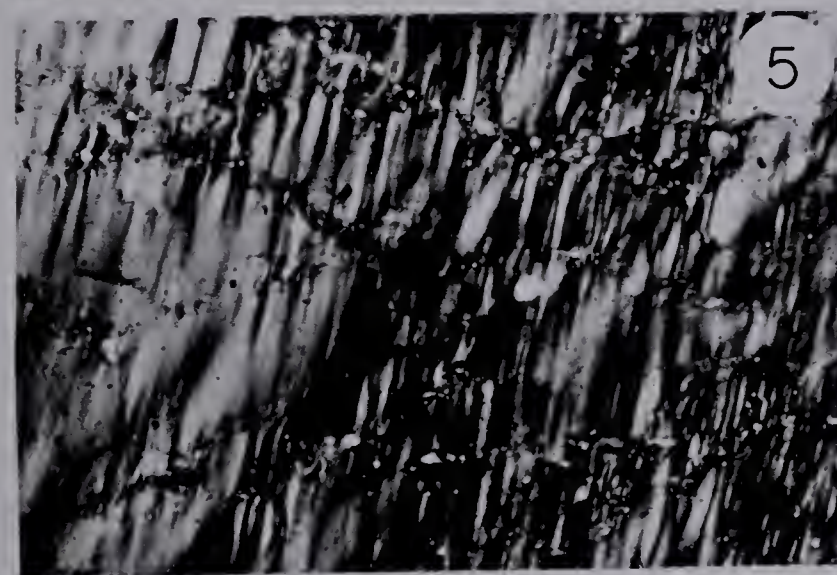
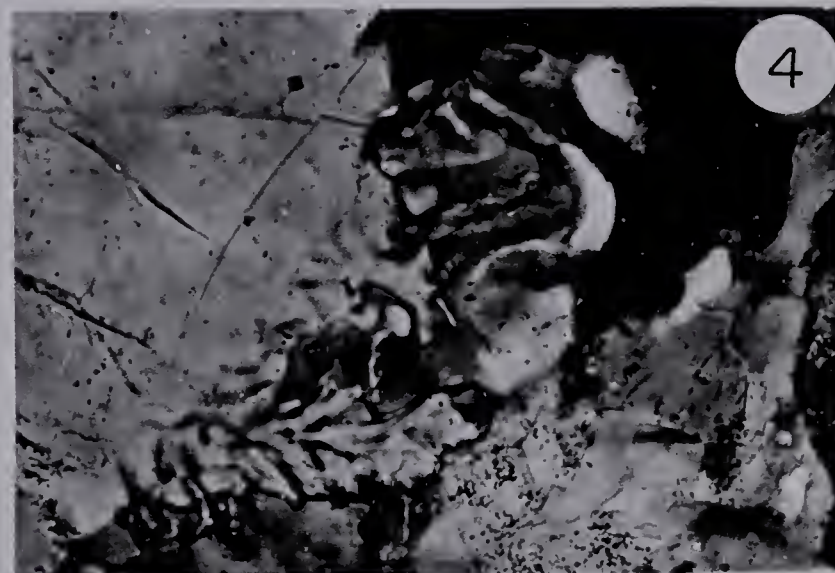
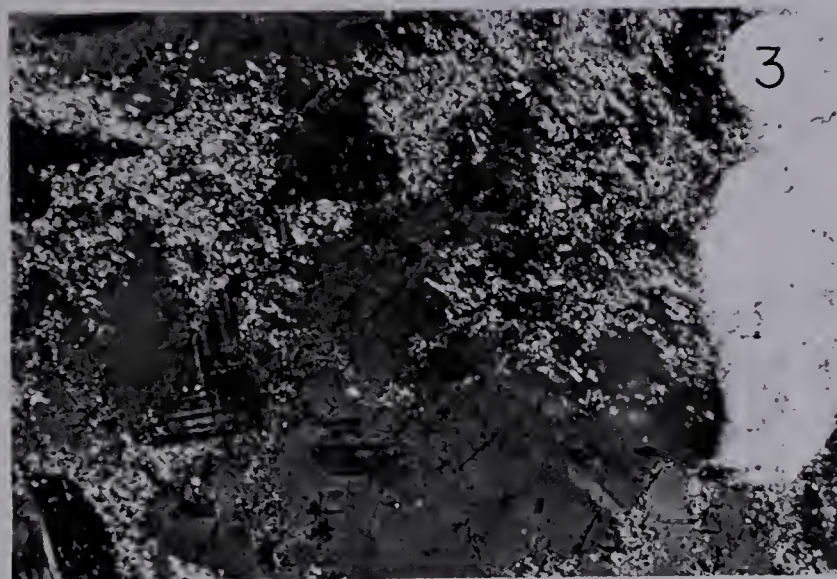
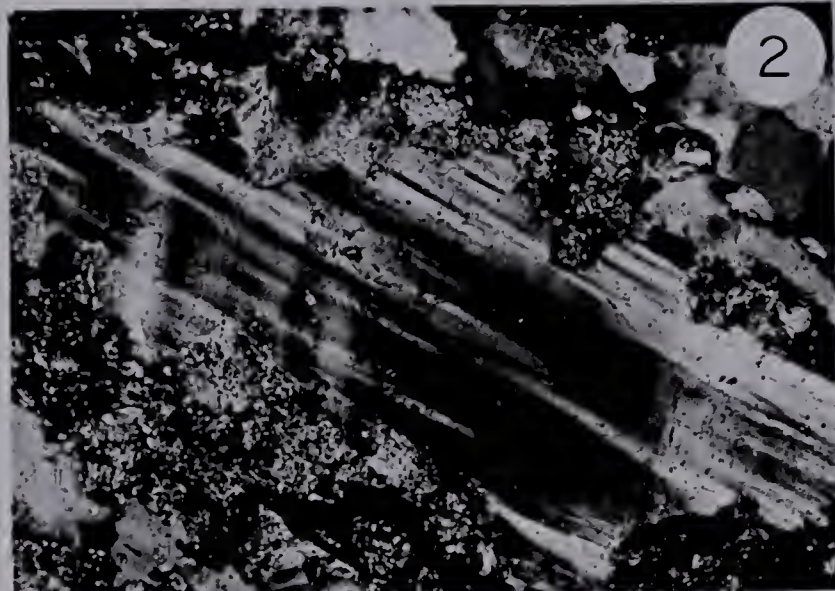
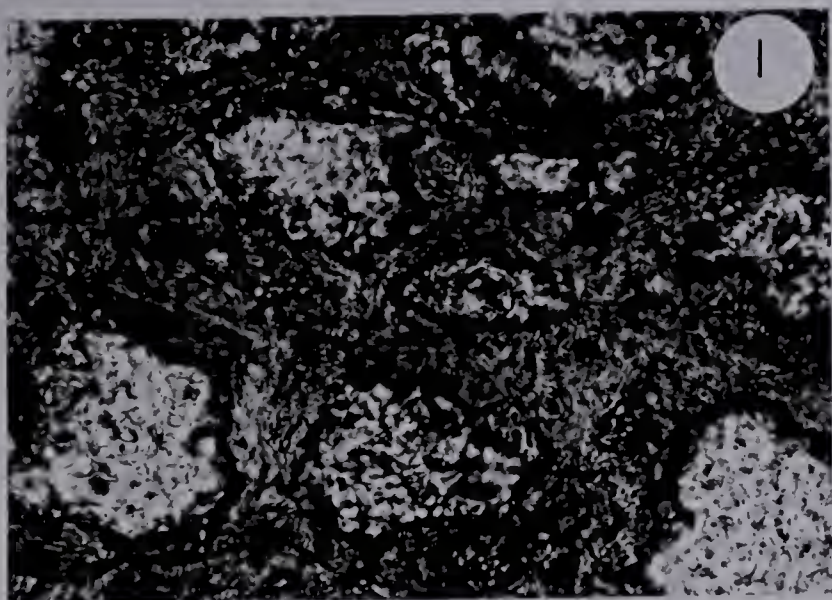
This specimen is light grey in color on both fresh and weathered surfaces. It is medium grained with some porphyroblasts of microcline and quartz. The rock is foliated, but compositional banding is not distinct. The specimen is composed of plagioclase ($\text{Ab}_{37}\text{An}_{63}$) 43 per cent, quartz 42 per cent, biotite 12 per cent, chloritic alteration products after biotite 2 per cent, microcline perthite 1 per cent.

The plagioclase in this specimen is not as strongly altered as in the other specimens of gneiss. Some of the plagioclase is veined and partially replaced by microcline.

R. B66-54 amphibolite

This rock is similar to specimen B66-26 but is less altered.

1. B66-15 Chlorite alteration products after garnet.
plane polarized light, x255.
2. B66-24 Microcline replacing altered plagioclase.
crossed nicols, x255.
3. B66-24 Microcline in quartz, both replacing altered
plagioclase. crossed nicols, x255.
4. B66-29 Myrmekite. crossed nicols, x400.
5. B66-49 Microcline braid perthite. crossed nicols,
x40.
6. B66-49 Microcline replacing altered plagioclase.
crossed nicols, x40.
7. B66-50 Microcline replacing plagioclase. crossed
nicols, x 40.
8. B66-52 Microcline and quartz replacing altered
plagioclase. crossed nicols, x40.



Microphotographs of selected textural features of specimens B66-15, B66-24, B66-49, B66-50 and B66-52. See overleaf for descriptions.

APPENDIX 2

METHODS OF CHEMICAL ANALYSES

1. Atomic Absorption

A Perkin-Elmer model 290 atomic absorption spectrophotometer with an attached Brush chart recorder was used to analyse for Cr, Ni, Ca, and Mn.

Approximately 1.5 grams of sample were weighed into a platinum dish. The sample was moistened with water, and 8 ml. hydrofluoric acid and 8 ml. of concentrated nitric acid added. The sample was decomposed on a hot plate and evaporated to dryness. The residue was moistened with water and 5 ml. concentrated nitric acid added. Evaporation to dryness was repeated twice. The residue from the previous step was taken up in 5 ml. of concentrated nitric acid and transferred to a 100 ml. beaker. This solution was warmed gently, filtered through a blue band filter paper into a 100 ml. volumetric flask, and diluted to volume. This solution was aspirated directly into the spectrophotometer for the Cr and Ni analysis. The Ni concentration was generally too low for a direct application of the atomic absorption method and an alternate method described on page 49 was used.

Mn analyses were made on aliquots extracted from the original solution and diluted to contain between 5 and 10 ppm Mn.

A multicomponent standard solution containing Cu, Mn, Ni, Cr, Fe, and Ca was used to prepare the standard curves for Cr, Mn, and Ni.

Ca analyses were made on aliquots extracted from the original solution and diluted to contain between 1 and 10 ppm Ca. The diluted aliquots contained 1 per cent La in order to suppress the quenching effect of phosphate.

The Ca analyses were difficult to reproduce. The $\text{La}(\text{NO}_3)_3$ solution added to suppress the quenching by phosphate clogged the capillary through which

the sample was aspirated into the instrument burner. The standard curve for Ca was reproducible only over a short period of time. Duplicate analyses made on specimens B66-26 and B66-56 by wet chemical methods indicate that the atomic absorption results for Ca are too high.

2. Colorimetric Analysis for Nickel

A colorimetric method suggested by Sandell, 1959, was used to analyse for Ni. The sample solutions prepared for the atomic absorption spectrophotometer were used.

An aliquot of the sample solution was measured into a 60 ml. separating funnel and 10 ml. of 10 per cent sodium citrate solution was added. The solution was made basic to the phenophalein end point by the addition of 1 : 1 NH_4OH . 3 ml. of α -furyl-dioxime in ethyl alcohol was added and the solution was agitated vigorously for 1 minute so the reaction could go to completion. A few ml. of chloroform was added to the separatory funnel and the mixture was agitated for 2 minutes to extract the organic Ni complex into the chloroform. The chloroform was then drawn off into another separatory funnel. The extraction was repeated twice until a total of 10 ml. of chloroform had been added. The combined extracts were shaken with 5 ml. of 1 : 30 NH_4OH and the chloroform solution was drawn off through glass wool into a cuvette. The absorption of the yellow Ni complex was then measured on a Beckman model B spectrophotometer at a wavelength of 435 $\text{m}\mu$. Chloroform was used as a reference solution.

A standard solution containing 1000 ppm Ni was prepared by dissolving 0.25003 gm. of Ni metal in nitric acid and diluting to 250 ml. Aliquots of this solution were used to make stock solutions of 1 to 10 ppm Ni. Aliquots of the stock solutions were used to prepare the standard curve for Ni. The points on the curve represent the best value of three or more extractions.

3. Analysis for the Alkali Metals

About 0.5 gram of sample was weighed into a platinum dish, moistened with water and 3 ml. of H_2SO_4 and 5 ml. HF added. The samples were decomposed on a hot plate and evaporated to dryness. The residue was ignited, first on a Tirrel burner, and then on a Meeker burner for 45 minutes. The ignited residue was moistened with 10 ml. of water and transferred to a 50 ml. beaker. This mixture was leached on a steam bath for 30 minutes and then decanted through a blue band filter paper into a 100 ml. volumetric flask. The leaching was repeated twice, each time with 10 ml. of water. The residue was then transferred to the filter paper and rinsed three times with water. The residue was transferred back to the platinum dish and 3 ml. 1 : 1 H_2SO_4 added. The entire procedure (evaporation, ignition and leaching) was repeated. The combined filtrates were diluted to volume.

The Na and K analyses were made directly on the solutions or on diluted aliquots of the solutions from above. The samples were aspirated directly into a Perkin-Elmer flame photometer and the emission measured. Stock solutions containing equal amounts of Na and K were used as standards.

The Cs analyses were made on a sample solution which had been adjusted to contain 500 ppm K. A 10,000 ppm K solution was used to adjust the K_2O concentrations so that dilution could be minimized. Stock solutions of Cs in the presence of 500 ppm K_2O were used as standards.

K analyses for the K-Ar age dating were made by precipitating $\text{KB}(\text{C}_6\text{H}_5)_4$. The K solutions were warmed to about 50°C . and an excess of sodium tetraphenylboron was added. The precipitate was allowed to stand for one to four hours. The solution was then filtered under vacuum through a pre-weighed, medium-pore fritted glass filter. The precipitate was dried in an oven for one hour and cooled in a desiccator for one-half hour. The filter plus precipitate

was then weighed, and the K content of the sample calculated from the difference in weight. No corrections were applied for coprecipitated Rb and Cs.

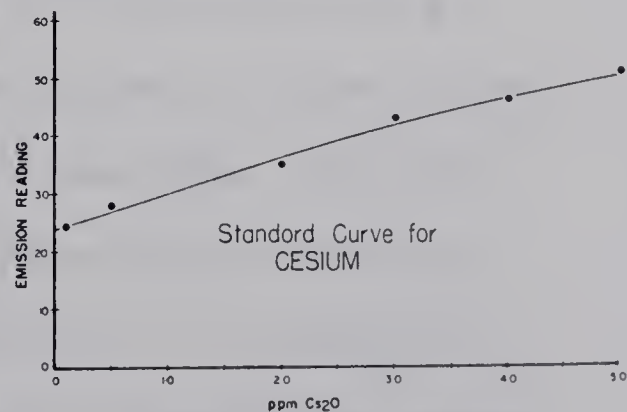
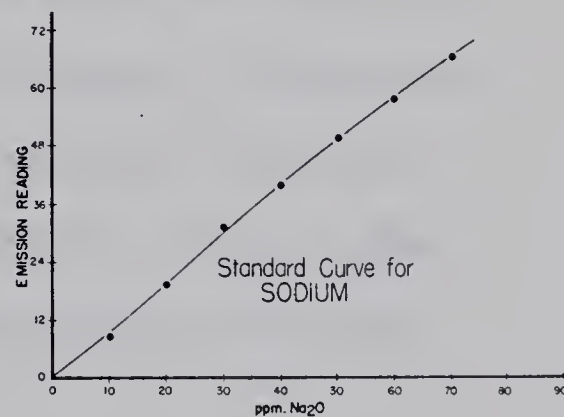
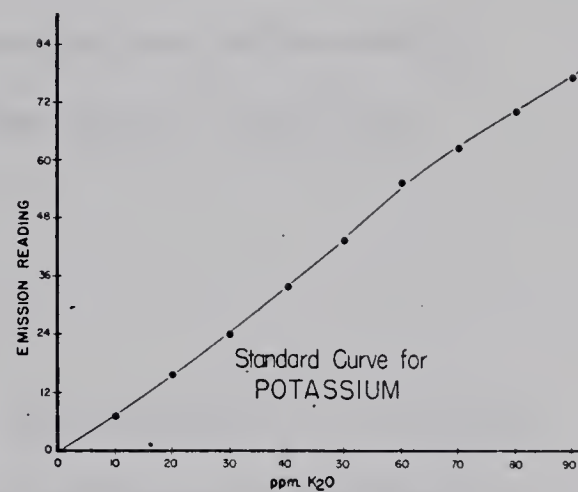
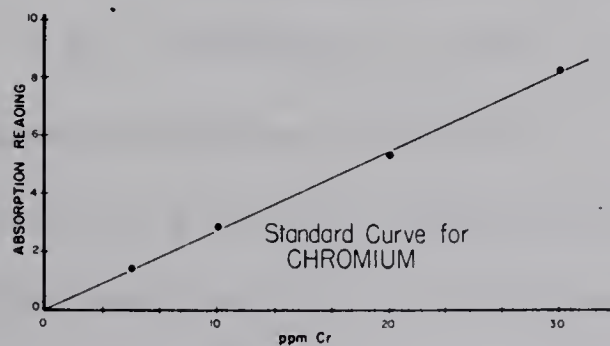
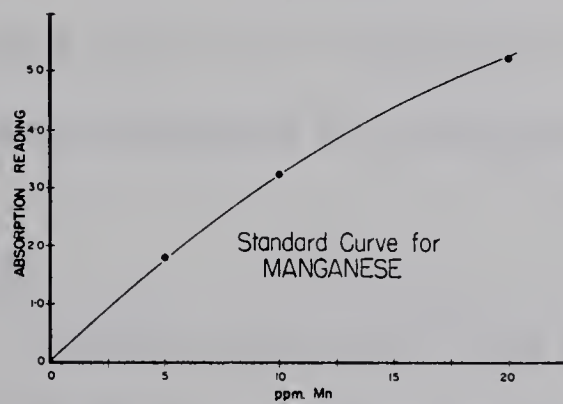
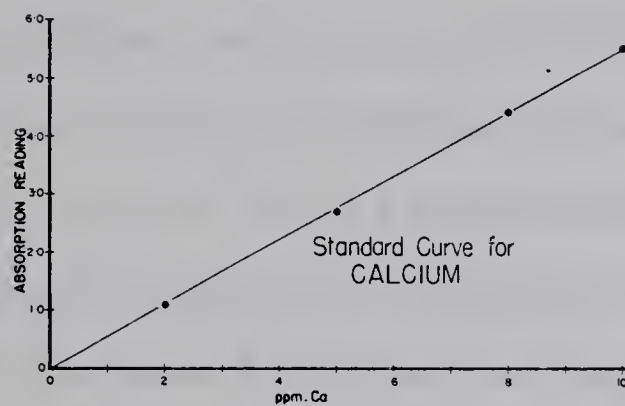
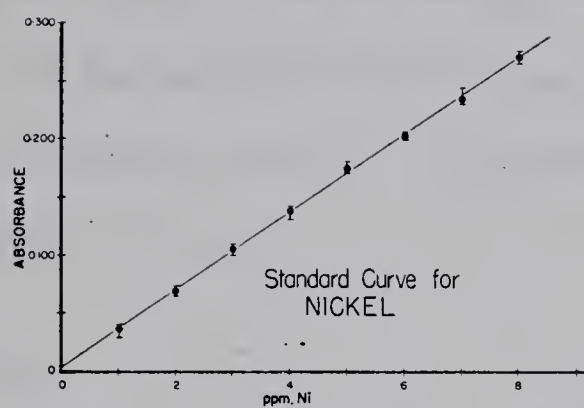


FIGURE 5. Standard Curves for Nickel, Calcium, Manganese, Chromium, Potassium, Sodium and Cesium

APPENDIX 3

Analytic Methods for Rb-Sr Age Determinations

1. Sample Preparation

The rock samples were trimmed of all weathered material and crushed, first in a jaw mill and then in a rotary crusher. The material from the rotary crusher was split 3:1, and the smaller fraction was ground to a fine powder in a blending mill. The approximate Rb and Sr compositions in the samples were determined by X-Ray Fluorescent analysis. The samples with the highest Rb to Sr ratios were selected for dating.

Rubidium

Sufficient sample to give a $\text{Rb}^{87}/\text{Rb}^{85}$ ratio of approximately 2 in the spiked mixture was weighed into a platinum dish and moistened with water. Five drops of H_2SO_4 , five ml. of HF and a precalibrated Rb spike was added. The sample was decomposed by heating on a hot plate and evaporated to dryness. The residue was ignited, first over a Tirrel burner and then over a Meeker burner for 30 minutes. The ignited residue was warmed gently and leached with a 2 ml. of water. The leachate was transferred to a small glass vial evaporated to dryness and stored.

Strontium

A sample containing sufficient Sr to give a $\text{Sr}^{88}/\text{Sr}^{86}$ ratio of less than 3 in the spiked mixture was weighed into a teflon beaker and moistened with demineralized water. 10 ml. of redistilled 1:1 HNO_3 and 10 ml. of HF were added. The solution was evaporated to dryness at 100–120°C. The residue was moistened with demineralized water and 5 ml. of 1:1 HNO_3 and evaporated to dryness. A few drops of demineralized water and 5 ml. of 1:1 HCl were added and the evaporation was repeated. The residue was baked for an hour, and then taken up in minimum of demineralized

water, transferred to a centrifuge tube and centrifuged to settle out any insoluble material. This solution was passed through a pre-calibrated ion-exchange column and the Sr fraction was collected in a small glass beaker. The Sr fraction was evaporated to dryness and stored.

The unspiked Sr samples were prepared in the same manner as the spiked samples except for the addition of the Sr spike.

2. Measurement of the Isotope Ratios

Tantalum wire filaments were used to load both the Rb and Sr samples. The filaments were enclosed in a small vacuum system, heated to incandescence and degassed for approximately 1 1/2 to 2 hours to remove any contaminant. The filaments were removed from the vacuum chamber and oxidized at atmospheric pressure before the samples were placed on the filaments.

The Rb sample was moistened with demineralized water, taken up in a fine-bore glass capillary tube and transferred to the tantalum filament (A small symmetrical load was found to run most smoothly). The filament was heated to dry the sample and then loaded directly into the mass spectrometer. Rb emission usually began at a filament current of 1.0 - 1.1 amperes. Measureable emission was usually obtained at a filament current of 1.3 - 1.5 amperes. K^{39}/K^{41} ratios were measured along with the Rb^{85}/Rb^{87} ratios to correct for mass discrimination. The K^{39}/K^{41} ratios were normalized to 13.71 and the Rb^{87}/Rb^{85} ratios were corrected by one-half of the K correction.

The Sr samples were loaded on tantalum filaments in the same manner as Rb. The filaments were then transferred to a small vacuum system where the samples were pre-treated at a current of approximately 2.0 amperes for about 12 - 14 hours before loading in the mass spectrometer. This treatment was usually sufficient to remove all of the alkali metals from the sample and so enhance the Sr emission. Sr emission usually began at a filament current of 2.1 - 2.2 amperes. Measurable emission

was usually obtained at a current of 2.3 - 2.5 amperes.

For the unspiked Sr samples it was necessary to measure the Sr^{88} , Sr^{87} and Sr^{86} peaks. For the spiked samples Sr^{88} , Sr^{87} , Sr^{86} , and Sr^{84} peaks were measured. Mass discrimination was corrected in the unspiked runs by normalizing the $\text{Sr}^{86}/\text{Sr}^{88}$ ratios to 0.1194 and correcting the $\text{Sr}^{87}/\text{Sr}^{86}$ by one-half of the $\text{Sr}^{86}/\text{Sr}^{88}$ correction. For the spiked Sr samples the mass discrimination was corrected by an iterative procedure using the $\text{Sr}^{88}/\text{Sr}^{86}$ and $\text{Sr}^{84}/\text{Sr}^{86}$ ratios. A calculation to illustrate the method is shown on pages 57-58.

The isotopic ratios were measured on a 6-inch 60-degree deflection solid source mass spectrometer with a single filament source and a single collector cup. Most of the Rb and Sr runs were recorded on a chart recorder. Some of the Sr runs were recorded by an integrating digital voltmeter. When using the digital voltmeter, the mass spectrometer scan was adjusted to the top of peaks and then switched from peak to peak by changing the magnet current. A minimum time of two seconds was required for the instrument to adjust from the top of the first peak to the top of the second. The digital voltmeter integrated the instrument output over one second and printed the results on chart paper. A chart recorder was used to follow the mass spectrometer output simultaneously and make certain the instrument did not drift off the top of the peak. Peak switching intervals of four to ten seconds were tried. Five seconds was found to be adequate. Twenty measurements or more were made for each peak in the set. The digital voltmeter required more stable emission than the chart recorder.

The isotope ratios were calculated from the digital voltmeter results by averaging two measurements on the top of one peak and dividing by the measurement of the second peak. In this method of calculation each measurement of a peak is used three times.

3. Example of Calculations

Sample B66-20

Ground whole rock

Measured Atomic Ratios

$$K^{39}/K^{41} = 13.783$$

normalized 13.71

$$Rb^{87}/Rb^{85} = 1.5830$$

$$\text{normalized} = Rb^{87}/Rb^{85}_{\text{meas.}} \times \left[\left(\frac{13.783}{13.71} - 1 \right) / 2 + 1 \right]$$

$$= 1.5872$$

$$Rb \text{ Spike Composition} = 1.9703 \mu\text{gm } Rb^{87}, 0.157 \mu\text{gm } Rb^{85}$$

$$\text{Normal Rb Composition } Rb^{87} = 27.85 \text{ per cent } Rb^{85} = 72.15 \text{ per cent}$$

$$\text{Weight of Rb Sample spiked} = \underline{0.1250 \text{ gm}}$$

$$Sr^{86}/Sr^{88}_{\text{unspiked}} = 0.1190 \text{ normalized} = 0.1194$$

$$Sr^{87}/Sr^{86}_{\text{unspiked}} = 0.7759 \text{ normalized} = 0.7746$$

$$Sr^{88}/Sr^{86}_{\text{spiked}} = 3.130$$

$$Sr^{87}/Sr^{86}_{\text{spiked}} = 0.3176$$

$$Sr^{84}/Sr^{86}_{\text{spiked}} = 0.3880$$

$$\begin{aligned} \text{Spike Composition} &= 1.419 \mu\text{gm } Sr^{88} & 0.3862 \mu\text{gm } Sr^{87} \\ &= 5.633 \mu\text{gm } Sr^{86} & 3.125 \mu\text{gm } Sr^{84} \end{aligned}$$

$$\begin{aligned} \text{Normal Sr Composition} &= 82.83 \text{ per cent } Sr^{88} \\ &= 6.96 \text{ per cent } Sr^{87} \\ &= 9.67 \text{ per cent } Sr^{86} \\ &= 0.54 \text{ per cent } Sr^{84} \end{aligned}$$

$$\text{Weight of Sr sample spiked} = 0.1424 \text{ gm}$$

Rubidium

$$Rb^{87}/Rb^{85}_{\text{measured}} \times 87/85 = \frac{\mu\text{gm } Rb^{87}_{\text{sp}} + \mu\text{gm } Rb^{87}_{\text{N}}}{\mu\text{gm } Rb^{85}_{\text{sp}} + \mu\text{gm } Rb^{85}_{\text{N}}}$$

$$1.5872 \times 87/85 = \frac{19.703 + \mu\text{gm Rb}^{87}_{\text{N}}}{0.157 + \mu\text{gm Rb}^{85}_{\text{N}}}$$

$$\mu\text{gm Rb}^{85}_{\text{N}} = 2.530 \quad \mu\text{gm Rb}^{87}_{\text{N}} \quad \therefore \mu\text{gm Rb}^{87}_{\text{N}} = 6.253$$

$$\text{ppm Rb}^{87} = \mu\text{gm Rb}^{87} / \text{sample weight} = 50.02$$

Strontium

$$\text{Sr}^{88}/\text{Sr}^{86} \text{ measured} \times 88/86 = \frac{\mu\text{gm Sr}^{88}_{\text{sp}} + \mu\text{gm Sr}^{88}_{\text{N}}}{\mu\text{gm Sr}^{86}_{\text{sp}} + \mu\text{gm Sr}^{86}_{\text{N}}}$$

$$\text{but } \text{Sr}^{88}_{\text{N}} = 0.8283 \text{ Sr}_{\text{N Total}}, \text{ and } \text{Sr}^{86}_{\text{N}} = 0.0967 \text{ Sr}_{\text{N Total}}$$

using these substitutions and solving for $\text{Sr}_{\text{N Total}}$

$$\text{Sr}_{\text{N Total}} = 32.053 \mu\text{gm}$$

$$\text{Sr}^{84}/\text{Sr}^{86} \text{ calculated} = \frac{(0.0054 \times 32.053) + \mu\text{gm Sr}^{84}_{\text{spike}}}{(0.0967 \times 32.053) + \mu\text{gm Sr}^{86}_{\text{spike}}}$$

$$\text{and } \text{Sr}^{84}/\text{Sr}^{86} \text{ calculated} = 0.377$$

$$\text{Mass discrimination} = \left[1 - \left\{ \text{Sr}^{84}/\text{Sr}^{86}_{\text{cal.}} \div (\text{Sr}^{84}/\text{Sr}^{86}_{\text{meas.}} \times 84/86) \right\} \right] \times 100$$

$$= 0.34 \text{ per cent}$$

The positive mass discrimination indicates that more of the heavier atoms have been removed by fractionation than lighter atoms. Thus the $\text{Sr}^{88}/\text{Sr}^{86}$ measured ratio is too low. To correct for this effect the $\text{Sr}^{88}/\text{Sr}^{86}_{\text{meas.}}$ is multiplied by 1.0034 and the $\text{Sr}_{\text{N Total}}$ is recalculated using this value. This iteration procedure is

continued until the calculated value of Sr_N^{Total} does not change. For the present calculation the iteration loop must be repeated four times before the circuit closes.

the result gives:

$$Sr_N^{Total} = 32.385 \text{ } \mu\text{gm and Mass Discrimination} = 0.66 \text{ per cent}$$

The Sr^{87*} is calculated from the equation

$$Sr^{87*} = \left\{ \left(\frac{87}{86} \times Sr^{87}/Sr^{86}_{\text{meas.}} \times \left(1 + \frac{M.D.}{2} \right) \right) \times (Sr^{86}_N + Sr^{86}_{sp}) \right\} - (Sr^{87}_N + Sr^{87}_{sp})$$

$$Sr^{87*} = 0.185 \text{ } \mu\text{gm} = 1.300 \text{ ppm}$$

$$Rb^{87}/Sr^{86} \text{ (atomic ratio)} = \frac{\text{ppm } Rb^{87}}{\text{ppm } Sr^{86}} \times 86/87 = 2.250$$

$$Sr^{87}/Sr^{86}_{sp} \text{ (atomic ratio)} = \frac{\text{ppm } Sr^{87}_N + \text{ppm } Sr^{87*}}{\text{ppm } Sr^{86}} \times 86/87 = 0.770$$

APPENDIX 4

The Single Coordinate in Error Regression Analysis

A least squares extrapolation plot was used to fit straight lines to the data obtained from the Rb and Sr analyses. This method assumes that the errors in the X-Coordinate values are negligible.

If the various points have coordinates $x_1y_1, x_2y_2, x_3y_3, \dots$ and are related by an equation of the form $Y = a + bx$, in general the line will not pass exactly through any of the points since each point is subject to random error. (This derivation is summarized from Davies, 1957, Chapter 7, p. 150-173).

If the value of y corresponding to $x = x_1$ is $a + bx_1$ and the first experimental point is $y = y_1$, then the error E_1 in this first point is given by $E_1 = (a + bx_1) - y_1$ and similarly for all other points. The sum of the squares of these errors is:

$$\sum E^2 = (a + bx_1 - y_1)^2 + (a + bx_2 - y_2)^2 + \dots \quad (1)$$

The best fit line is that line which makes the sum of squared errors a minimum. If equation 1 is differentiated with respect to a , and the result equated to 0

$$\frac{d \sum E^2}{da} = 2(a + bx_1 - y_1) + 2(a + bx_2 - y_2) + \dots = 0$$

$$\text{or } \sum a + b \sum x - \sum y = 0 \quad (2)$$

The best value of b is found by differentiating equation 1 with respect to b and equating to 0

$$\frac{d \sum E^2}{db} = 2x_1 (a + bx_1 - y_1) + 2x_2 (a + bx_2 - y_2) + \dots = 0$$

$$\text{or } a \sum x + b \sum x^2 - \sum xy = 0 \quad (3)$$

Equations 2 and 3 are called the normal equations and can be rearranged to:

$$\sum y = \sum a + b \sum x \quad (4)$$

$$\sum xy = a \sum x + b \sum x^2 \quad (5)$$

Equations 4 and 5 can be solved simultaneously to give the best fit values of a and b.

The variance is the square of the standard deviation. The variance about the line is estimated by

$$S^2 = \sum (y - a + bx)^2 / n-2 \quad (6)$$

where n is the number of points.

The standard error in slope is defined as:

$$S. E. = S / \sqrt{\sum (x - \bar{x})^2} \quad (7)$$

Equations, 4, 5, 6 and 7 were used to calculate the slopes of the isochrons and the standard errors in the slopes.

MacIntyre et al, 1967, has pointed out that the method described above is not mathematically rigorous because the errors in X are not negligible but increase with X. However, in the present case, the scatter of points about the regression lines appear to be much greater than can be accounted for by random analytical errors, and a more rigorous calculation would not be any more meaningful. The more rigorous calculation which assumes errors in both coordinates would probably give a larger standard error in the slope of the regression line.

108° 20' 11"
59° 36' 17"

59° 33' 45"
108° 20' 11"

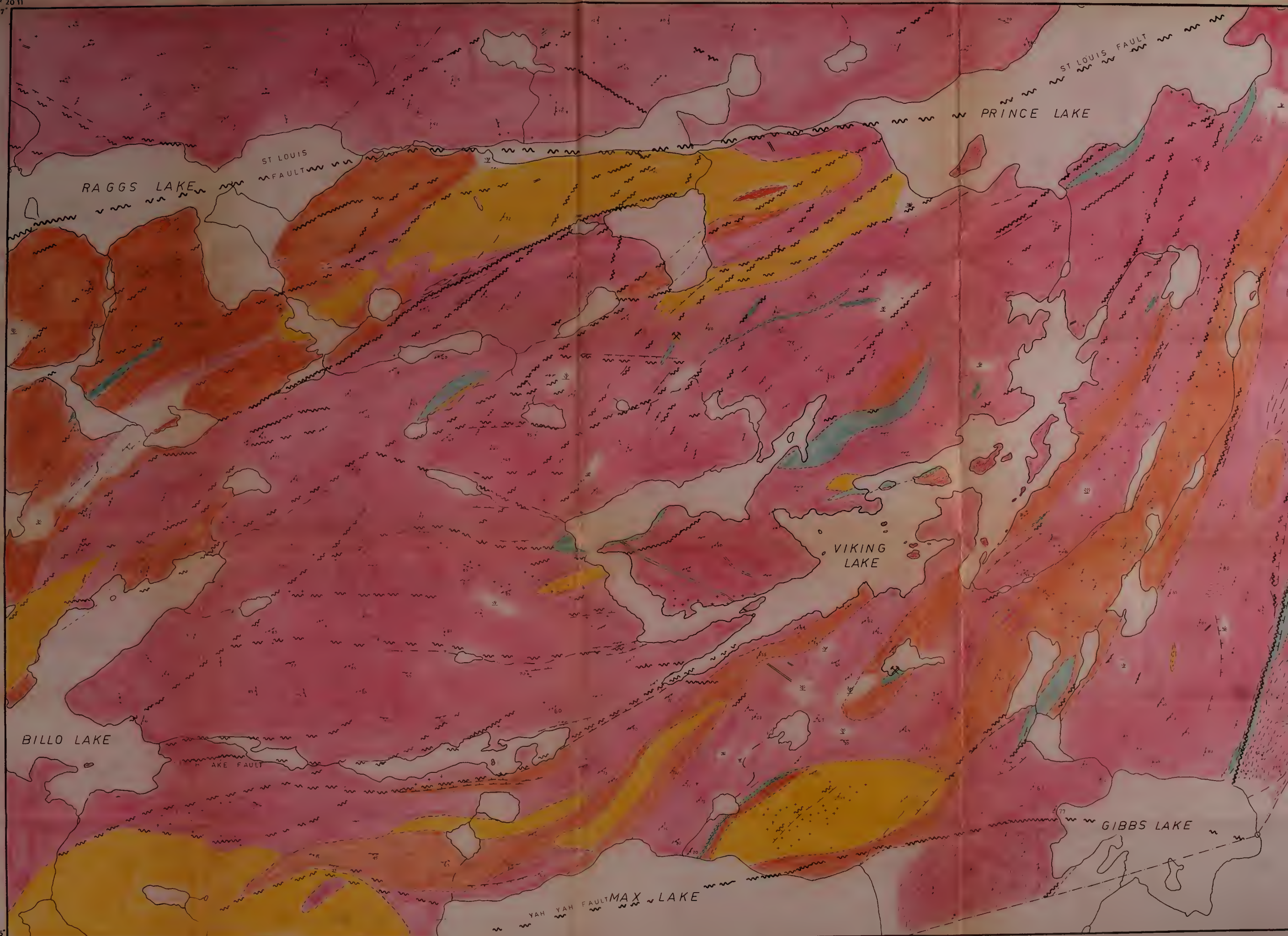
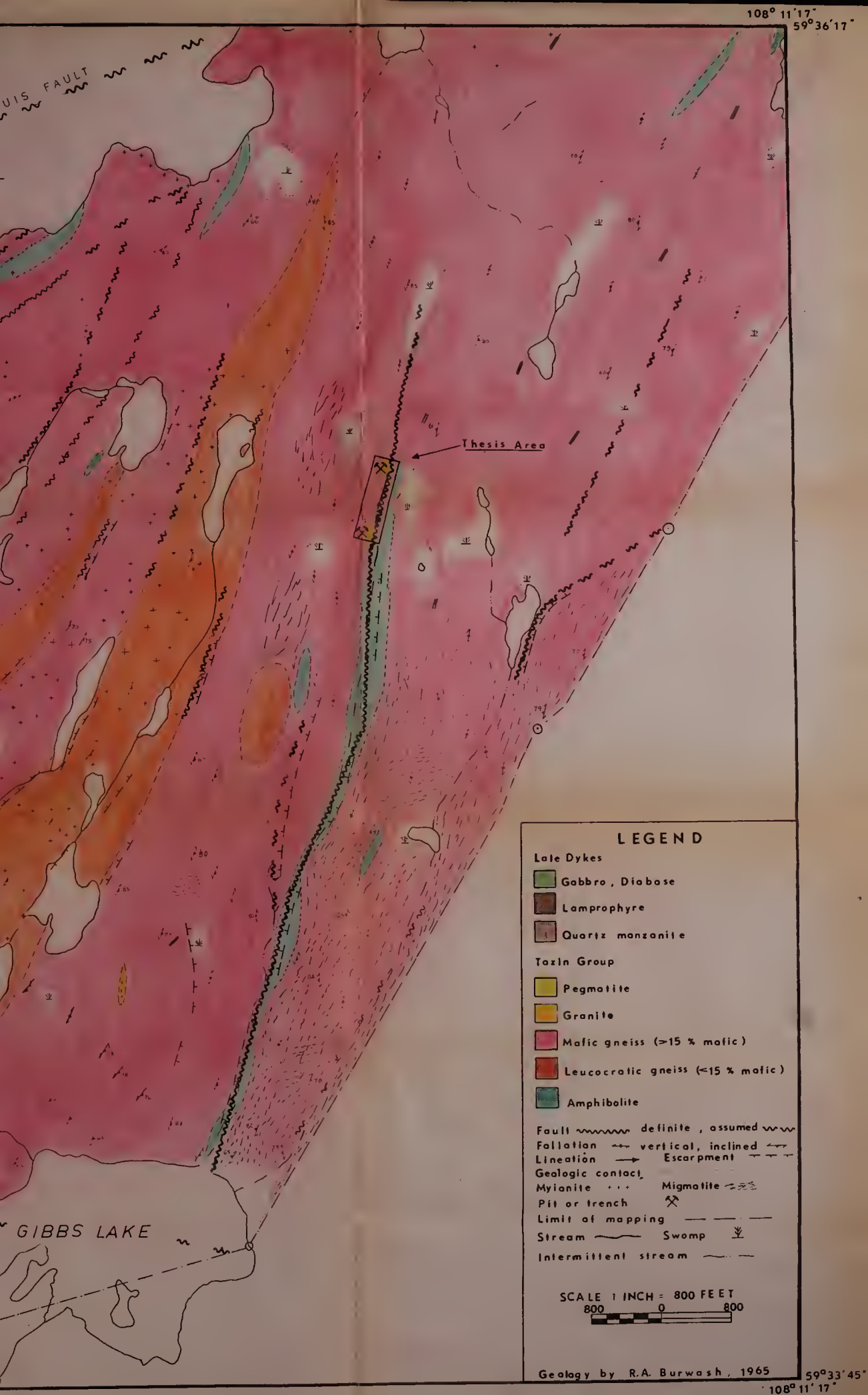


FIGURE 2 GEOLOGY OF THE VIKING LAKE AREA



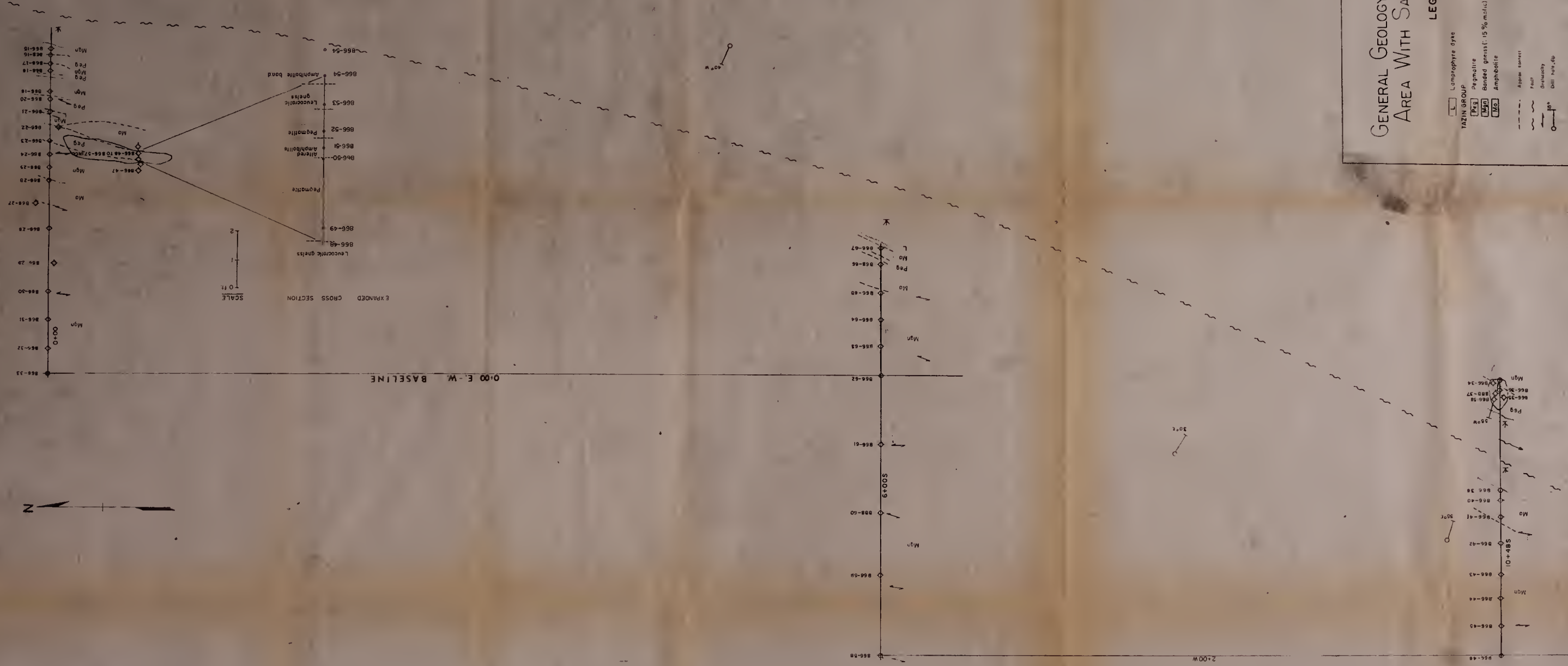


FIGURE 3

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